MOVING STRIATIONS AND ANODE EFFECTS IN AN ARGON GLOW DISCHARGE

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Submitted in partial fulfillment of
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ABSTRACT

Moving striations and anode oscillations were studied over a wide range of gas pressures and discharge currents in an argon glow discharge. Striation spacing, frequency and velocity were measured as a function of discharge current from low currents to the current for extinction of moving striations, for pressures from 1 to 16 mm Hg. Striation frequency was also measured as a function of pressure for various radii discharge tubes.

The anode spot light oscillations were eliminated by use of an auxiliary anode discharge, which brought the positive column in contact with the anode and eliminated the oscillating anode fall in potential. This change in the anode region produced no significant change in the striation parameters, but greatly reduced and altered the frequency of the potential oscillations across the discharge tube. The potential oscillations now followed the wave form and frequency of the striation oscillations instead of the frequency of the anode spot oscillations.

By use of a discharge tube, constructed with sections of different radius, moving striations in the positive column were isolated from both cathode and anode by sections of homogenous positive column in which no voltage oscillations were detectable by floating probes. This leads to the conclusion that striations are due to an inherent instability of the positive column, and not to the effects developed by the anode or cathode.

TABLE OF CONTENTS

Section	Title	Page
1.	INTRODUCTION	
	1.1 History.	1
	1.2 Characteristics of a Glow Discharge.	1
	1.3 Previous Experimental Work.	3
	1.4 Previous Theoretical Work.	4
2.	EXPERIMENTAL EQUIPMENT AND PROCEDURES	
	2.1 Vacuum System.	10
	2.2 Electronic Circuits.	12
	2.3 Discharge Tube Construction.	13
	2.4 Pupp's Anode Operation.	21
	2.5 Frequency Measurement Procedures.	24
	2.6 Wavelength Measurements.	27
3.	OBSERVATIONS AND ANALYSIS OF STRIATION PARAMETERS	
	3.1 Frequency.	30
	3.2 Wavelength.	43
	3.3 Velocity.	46
	3.4 Voltage Drop Across the Discharge Tube.	50
4.	OBSERVATIONS AND ANALYSIS OF PUPP'S ANODE TECHNIQUE	
	4.1 Effects on Moving Striations.	54
	4.2 Effects on Tube Voltage Oscillations.	57
	4.3 Effects upon Probe Oscillations.	60
	4.4 Summary.	62
5.	OBSERVATIONS AND ANALYSIS OF ISOLATED STRIATIONS	
	5.1 Background.	65
	5.2 Striations Isolated From Both Anode and Cathode.	67

TABLE OF CONTENTS (Contd)

Section	Title	Page
5.	OBSERVATIONS AND ANALYSIS OF ISOLATED STRIATIONS (Contd)	
	5.3 Voltage and Probe Oscillations.	67
	5.4 Summary.	73
6.	CONCLUSIONS	
	6.1 Conclusions.	76
	6.2 Recommendations for Further Work.	77
	6.3 Acknowledgments.	78
7.	BIBLIOGRAPHY	79

LIST OF ILLUSTRATIONS

Figure		Page
1.	A Glow Discharge.	2
2.	Oscillator Frequency versus Striation Frequency.	8
3.	Block Diagram of Vacuum System.	11
4.	Block Diagram of Electronic Circuits.	14
5.	General View of Discharge Tube and Vacuum Systems.	17
6.	Electronic Equipment.	18
7.	Electronic Equipment.	19
8.	Discharge Tubes.	20
9.	Electrode Types.	22
10.	Photomultiplier Trace for Frequency Measurements.	26
11.	Rotating Mirror Photograph for Wavelength Measurement.	26
12.	Oscilloscope Photograph of Two Photomultiplier Traces in Phase.	26
13.	Rotating Mirror.	28
14.	Plot of Frequency versus Pressure.	32
15.	Plot of Frequency versus Pressure.	33
16.	Plot of Frequency versus Pressure.	34
17.	Plot of Frequency versus Current.	35
18.	Plots of Frequency versus Current.	36 - 38
19.	Plot of Frequency versus Current.	40
20.	Plot of Radius x Pressure versus Radius x Frequency.	41
21.	Plot of Wavelength versus Current.	44
22.	Plot of Wavelength versus Current.	45
23.	Plot of Velocity versus Current.	47
24.	Plot of Velocity versus Current.	48

Figure		Page
25.	Plots of Velocity versus Pressure.	49
26.	Plot of Voltage versus Current.	51
27.	Plot of Voltage versus Pressure.	52
28.	Light Oscillations of Anode Spots and Moving Striations	55
29.	Photomultiplier Tracings of Moving Striations with and without Pupp's Anode Operating.	55
30.	Plot of Frequency versus Current.	58
31.	Plot of Wavelength versus Current.	58
32.	Plot of Frequency versus Current.	59
33.	Phase relation between Anode Spot Light Oscillations and Tube Voltage Oscillations.	61
34.	Wave form correspondence between moving striations and tube Voltage Oscillations with Anode Spots Extinguished.	61
35.	Absence of Both Moving Striations and Tube Voltage Oscillations when Anode Spots are Extinguished.	61
36.	Oscilloscope Traces of Striations, Probe Oscillations, and Tube Voltage Oscillations; Anode Spots present.	63
37.	Oscilloscope Traces of Floating Probe Potentials.	63
38.	Step tube used by A W Cooper.	66
39.	Step tube used in this experiment.	66
40.	Rotating Mirror Photograph of Isolated Striations.	68
41.	Rotating Mirror Photograph of Moving Striations.	68
42.	Oscilloscope Traces; Striations Throughout Tube.	70
43.	Oscilloscope Traces; Striations in Large Section Only.	72
44.	Oscilloscope Traces; Striations in Narrow Band of Large Section Only.	74
45.	Oscilloscope Traces; No Striations Present in Tube.	75

1. INTRODUCTION

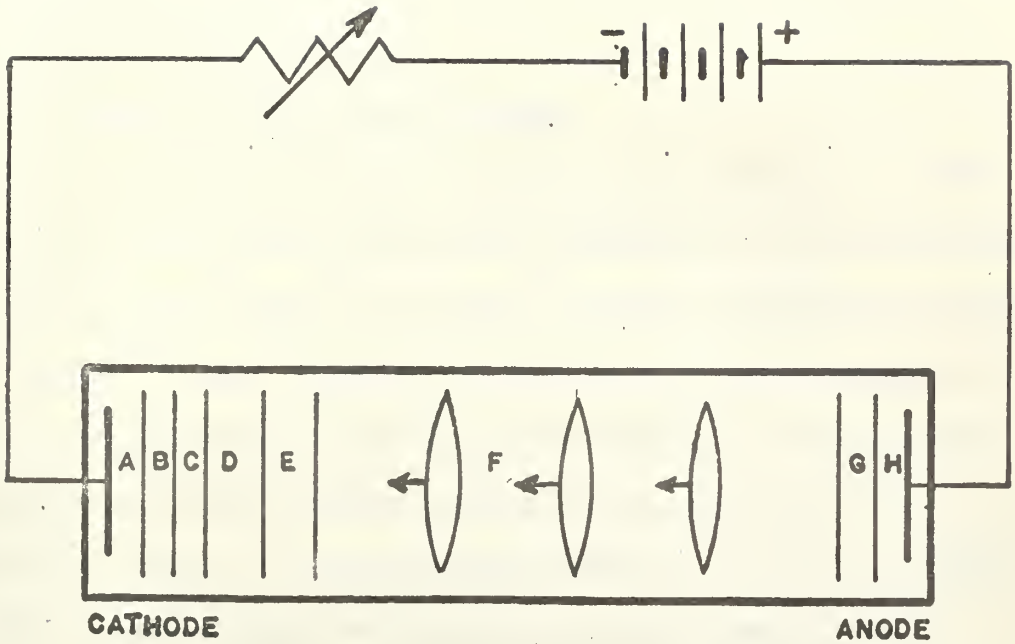
1.1 History.

Since the discovery of moving striations in the positive columns of glow discharges, in the rare gases and mercury vapor, by Wüllner in 1874 (1), the phenomenon has been the target of various investigators and now 87 years later no adequate theory exists. The quest for an adequate theory of moving striations has intensified during the past few years as it has become apparent that the most promising source of a controlled fusion reaction is in a plasma at high temperatures. To date, it has been impossible to maintain sufficient stability of a plasma to reach the necessary high temperatures. A basic theory of a plasma appears to be necessary for the development of a technique of attaining this stability. No such theory will be complete that does not adequately explain the existence of moving striations.

1.2 Characteristics of a Glow Discharge.

The characteristic regions of a typical glow discharge in an inert gas are shown in Figure 1. The glow discharge is produced by placing a high potential across a tube containing a gas at a few millimeters of mercury pressure thus causing a current to flow through the gas. The visible light (glow) is produced by electron transitions in atoms and ions excited by collisions.

The widths and relative light intensities of the characteristic regions of the discharge are dependent upon the tube geometry, gas pressure, applied voltage, discharge current and type of gas present.



a. Aston Dark Space.

b. Cathode Glow.

c. Cathode Dark Space.

d. Negative Glow.

e. Faraday Dark Space.

f. Positive Column (with moving striations).

g. Anode Glow.

h. Anode Dark Space.

FIGURE 1 A glow discharge (2)

These investigations are primarily concerned with the positive column and anode regions of the discharge. Over considerable ranges of current and pressure the positive column is observed to have bands of relatively high light intensity which travel from the anode to the cathode. These bands of high light intensity followed by areas of low light intensity are referred to as moving striations.

The anode glow is the region of the anode fall in potential. This region is usually found to be unstable resulting in anode light oscillations which are often referred to as "anode spots." With the types of electrodes used in our

investigations the anode fall region was unstable under normal discharge conditions.

1.3 Previous Experimental Work.

Early investigators such as Aston and Kikuchi (3) and Pupp (4) used rotating mirrors and photocells, in conjunction with oscilloscope traces, to study the basic parameters (frequency, velocity, and separation distance or wavelength) of the moving striations in the positive column. It might be well to mention here that the positive column of a non-striated discharge is a good approximation to a true plasma since the concentration of positive ions is very nearly equal to the concentration of electrons and negative ions. Pupp (5) also made extensive investigations into the region of the anode fall in potential. In the late 1940's, Donahue and Dieke (6, 7) also made extensive investigations into the basic parameters of the moving striations in the positive column.

Pupp, and Donahue and Dieke, carried out investigations in various regions of pressure, discharge current, and tube radius. This investigation covers wider regions of pressure, current, and tube radius in an effort to tie together this earlier data and reconcile some apparent contradictions. Using Pupp's technique, of an auxiliary discharge at the anode, investigations were made into the effects of the anode oscillations upon the basic parameters of moving striations. Utilizing the dependence of critical current, for the elimination of moving striations in the positive column, upon the tube radius, a varying radius tube

was constructed to allow the isolation of moving striations from both anode and cathode. This technique yielded considerable information as to the possible origin of moving striations.

Aston and Kikuchi proposed, in an empirical relation, that the velocity of the moving striations was proportional to the reciprocal of the gas pressure. Whiddington (8) proposed that the velocity of the moving striations was proportional to the reciprocal of the square root of the gas pressure. An attempt is made in this work to determine the validity of these relations.

1.4 Previous Theoretical Work.

Various theoretical attempts have been made to explain the presence of moving striations in the positive column. Of these attempts only Gordeev (9) claims an accurate theoretical description of striation parameters. This paper is limited to prediction of the frequency of the moving striations only. Gordeev postulates that both positive (Anode to Cathode) and negative (Cathode to Anode) moving striations are a direct result of electron oscillations. The positive striations are a wave group initiated by electrons changing velocity in the region of the anode fall. The negative striations are reflections of the positive striations in the negative glow or at the cathode.* Gordeev presents equations for calculation of permissible frequencies of both positive and negative striations in terms of electron temperature,

*In the available translation of this work some confusion as to the exact meaning existed. Both possible interpretations are indicated.

electron concentration and electron drift velocity. These parameters were not measured in our work, therefore no quantitative check of these relations is made. Qualitative information is obtained in relation to the mechanism proposed.

Donahue and Dieke (6) suggest, as a tentative mechanism, that the negative striations originate in the negative glow region near the cathode and are triggered by approaching positive striations. The positive striations are initiated in the region of the anode. Dieke and Donahue observed that positive striations always leave the anode at a time when the voltage across the discharge tube is a maximum, and suggested that the striations resulted from a build-up of a large cloud of ions in front of the anode. They related this build-up of ions directly to the anode oscillations and discharge tube voltage (current) oscillations.

Coulter, Armstrong, and Emeleus (10) conducted experiments with moving striations in a discharge passing through two different tube radii. They called the boundary between the moving striations of the two sections a "virtual anode." From these experiments they concluded that moving striations can originate at oscillating anode spots. However, they did not show that anode spots need be present for the production of moving striations.

Allis (11) also believes that moving striations have their origin at the oscillating anode spots. The electrons coming through the sheath of positive ions in front of the anode will cause an over concentration of ions by ionizing the more easily ionized gas molecules which have already been

excited to metastable states. This accumulation of excess positive charge must then move away from the anode toward the cathode, at approximately the ion velocity, thus producing moving striations.

Takamine, Suga, and Yanagihara (12) used a falling plate camera to show a relationship between moving striations and anode spots. They found the usual type of moving striations, but also found that they coincided with oscillations of the anode spots and that the striations originated at the anode spots. It appears, from their work, that moving striations start as pieces of anode spot which break away with a given frequency.

Watanabe and Oleson (12) show that there can exist, in a positive column, traveling waves of ion and electron density. They do not identify these waves as moving striations. They establish mathematically the possibility of these moving density waves existing in the positive column by use of the diffusion equations.

Robertson (13) considers, in general terms, a longitudinally uniform and axially symmetric positive column which may be excited by some external oscillatory force. This external source might be the cathode or cathode region as proposed by Loeb (14). Robertson proposes that a stable, homogeneous positive column may not exist at all, and that the instability resulting in striations may originate in the positive column itself.

In his development he considers production and loss of positive ions and metastable atoms as well as their

concentrations using modified continuity equations containing production and loss terms. He considers ionization taking place by direct electron impact and by two stage processes involving metastable states.

Predictions from his theory are only approximate and no quantitative results are given. Qualitatively, both positive and negative striations are predicted to exist with a lower limit to the velocity of the negative striations. The important weaknesses of this theory, as stated by the author, are the use of a small perturbation theory and the lack of reliable expressions for ionization and excitation rates.

The oscillating anode fall region (anode spots) was investigated in detail by Pupp (5). Pupp used an auxiliary discharge, without positive column, within the anode to furnish a controlled source of ion production at the anode. Pupp was thus able to study the anode fall region under various degrees of positive and negative anode fall. These experiments demonstrated the dependence of the anode fall, and thus the anode oscillations, upon the rate of ion production at the anode.

Pupp proposed that the anode oscillations were the result of a build-up in positive ion concentration at the anode which causes ions to move away from the anode due to the influence of the nearest longitudinal field. Electrons will now be accelerated into this anode drop, resulting in increased production of ions. The ion concentration at the anode builds up again and the cycle repeats periodically.

These anode oscillations are usually observed at more than one location on the anode.

From his experiments with the artificial ion source at the anode Pupp concluded, without too much explanation, that the moving striations in the positive column had nothing to do with the disturbances due to the anode oscillations and that the moving striations must be due to the instability of the plasma forming the positive column.

Zaitsev (15) takes the opposite view and proposes that, in some cases at least, the moving striations are the result of disturbances in the positive column due to the anode oscillations.

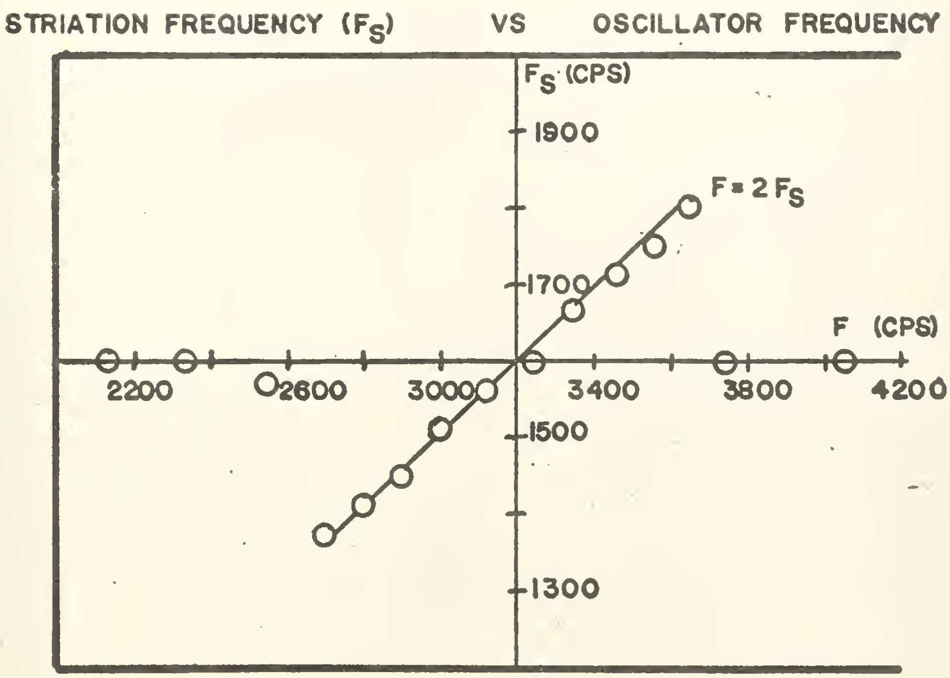


FIGURE 2
Oscillator Frequency versus Striation Frequency

Experiments performed by Cooper (16) show that an external disturbance applied to the anode could affect the frequency of moving striations. A signal of 2200 to 4200 cycles per second from an external signal generator, was applied to the anode of an argon glow discharge. As can be seen

from Figure 2 above the striation frequency was driven over changes of 30% of its natural value through a portion of the range. It was decided that the role of the anode oscillations needed to be further clarified in the course of these investigation.

2 Experimental Equipment and Procedures

2.1 Vacuum System

A schematic diagram of the vacuum system is shown in Figure 3. The vacuum system, which was constructed by A W Cooper in December 1959, is primarily designed for frequent and rapid changes of discharge tubes. This was a principle requirement because of the frequent filament replacement required and the different types of tubes to be included in these investigations. To meet this requirement, it was necessary to abandon hope for pressures down to 10^{-8} and 10^{-9} mm Hg. The price to be paid for flexibility was additional stopcocks; more bends, branches, and constrictions in the glass tubing; and, of course, a larger volume to be evacuated.

A portable bakeout oven was constructed by the physics shop that would break down into four sections for ease of handling. Before data were taken, the discharge tube was baked for 12 to 24 hours at 400°C. Pressures usually attained were normally in the middle of the 10^{-7} mm range. Pressure was measured with a Consolidated Electrodynamics Corp. Ionization Gauge, type DPA-38, for high vacuum measurements.

A higher vacuum might have been desired to insure greater purity of the discharge, but since the experiments were all conducted with a directly heated Cathode, the advantage of an initially higher vacuum is questionable.

Dissolved gases in the surfaces of the electrodes were driven off by using a Scientific Electric Co. Induction heater, Model AC-5-LB, to heat the metal to a bright red-orange color. Final purification was achieved by running a

VACUUM SYSTEM

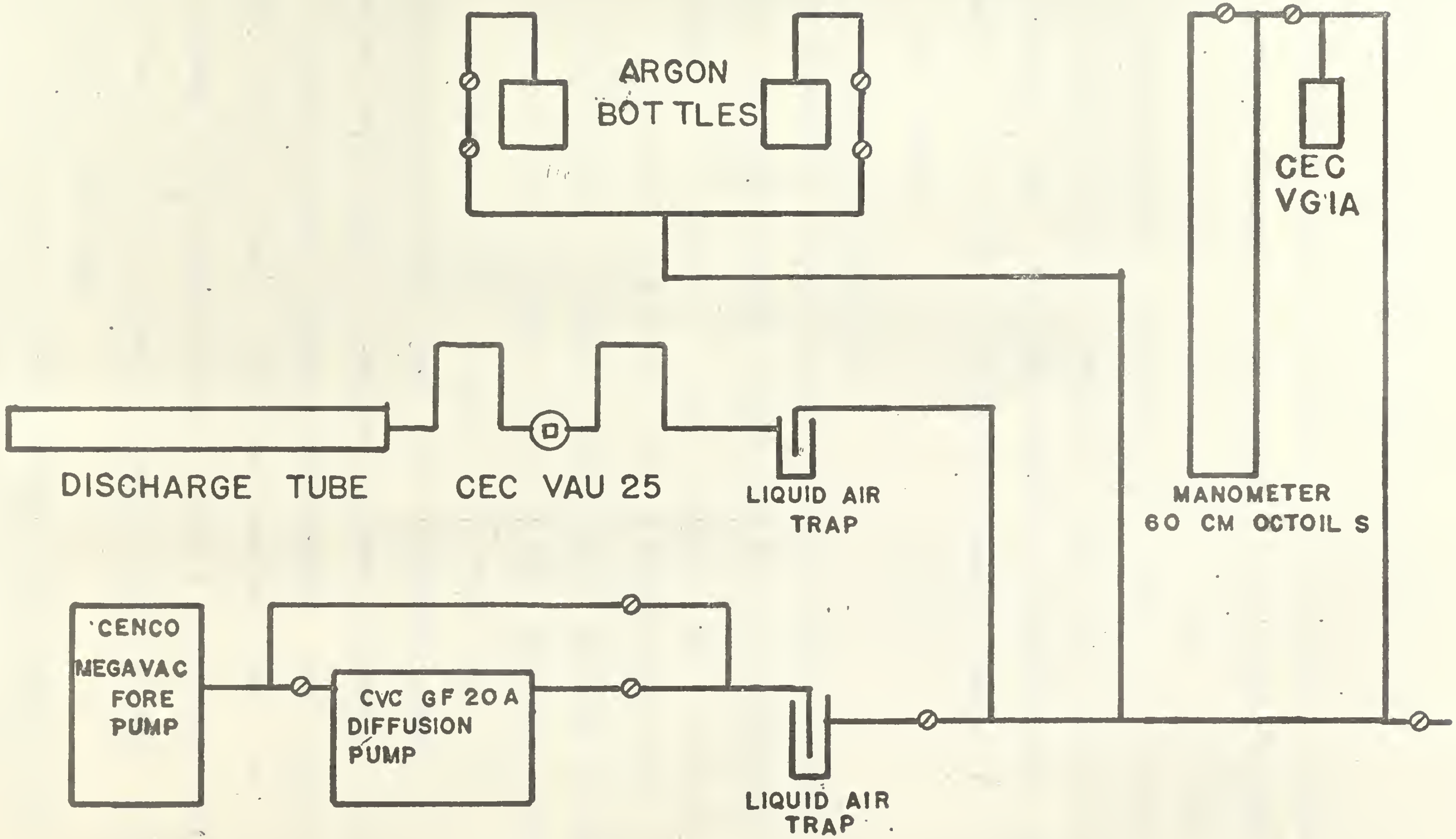


FIGURE 3

discharge for several minutes and then pumping down to a high vacuum (repeating this procedure several times).

The system provided for the attachment of two, 1-liter Linde high purity rare gas bottles. This provided a spare bottle of argon sealed in the system, or provided for the alternate use of another inert gas such as neon. The discharge tube was filled by bleeding the inert gas, by means of a double stopcock system, through a liquid air trap into the main discharge tube. The gas pressure in the discharge tube was measured with a 60 cm Octoil-S manometer (one cm oil equals 0.672 mm Hg).

2.2 Electronic Circuits

The schematic of the general circuit layout is shown in figure 4. The high voltage supply for the main discharge had to be capable of supplying a well regulated DC current up to 2 amps, to cover the discharge current range objectives for these investigations. A Kepco, model 770B, voltage regulated power supply, having a range of 0-2.25 amp, 600 volt maximum output (voltage regulated to within 0.1 volt) was used.

Three resistor banks, each with different ranges of resistance, were needed in series with the discharge tube to handle the wide current ranges investigated. For currents less than 100 ma, a zero to 65k-ohm bank was used; for currents between 100 ma and 1000 ma, a zero to 1760 ohm resistor bank was used; and for currents greater than one amp, a zero to 400 ohm bank was used.

The filaments were normally heated with a Kepco Magnetic-Tubeless, voltage regulated, Power Supply with a

current capability of zero to 15 amps at voltages of zero to 36 volts (voltage regulated to 25 mv). There was a small amount of ripple from this power supply that made the use of storage cells necessary for a few more sensitive measurements. The storage cells were not desirable for general use because a drop in voltage occurs resulting in a current drop during long periods of operation.

The power supply for the auxiliary discharge in the anode was a Sorensen B-Nobatron, model 1000 BB with a maximum DC current output of 500 ma with a voltage output of 200 to 1000 volts (voltage regulated to 0.5%). Figures 5, 6, and 7 show photographs of the physical layout of the equipment.

2.3 Tube Construction

Figure 8 shows the details of construction of the discharge tubes used.

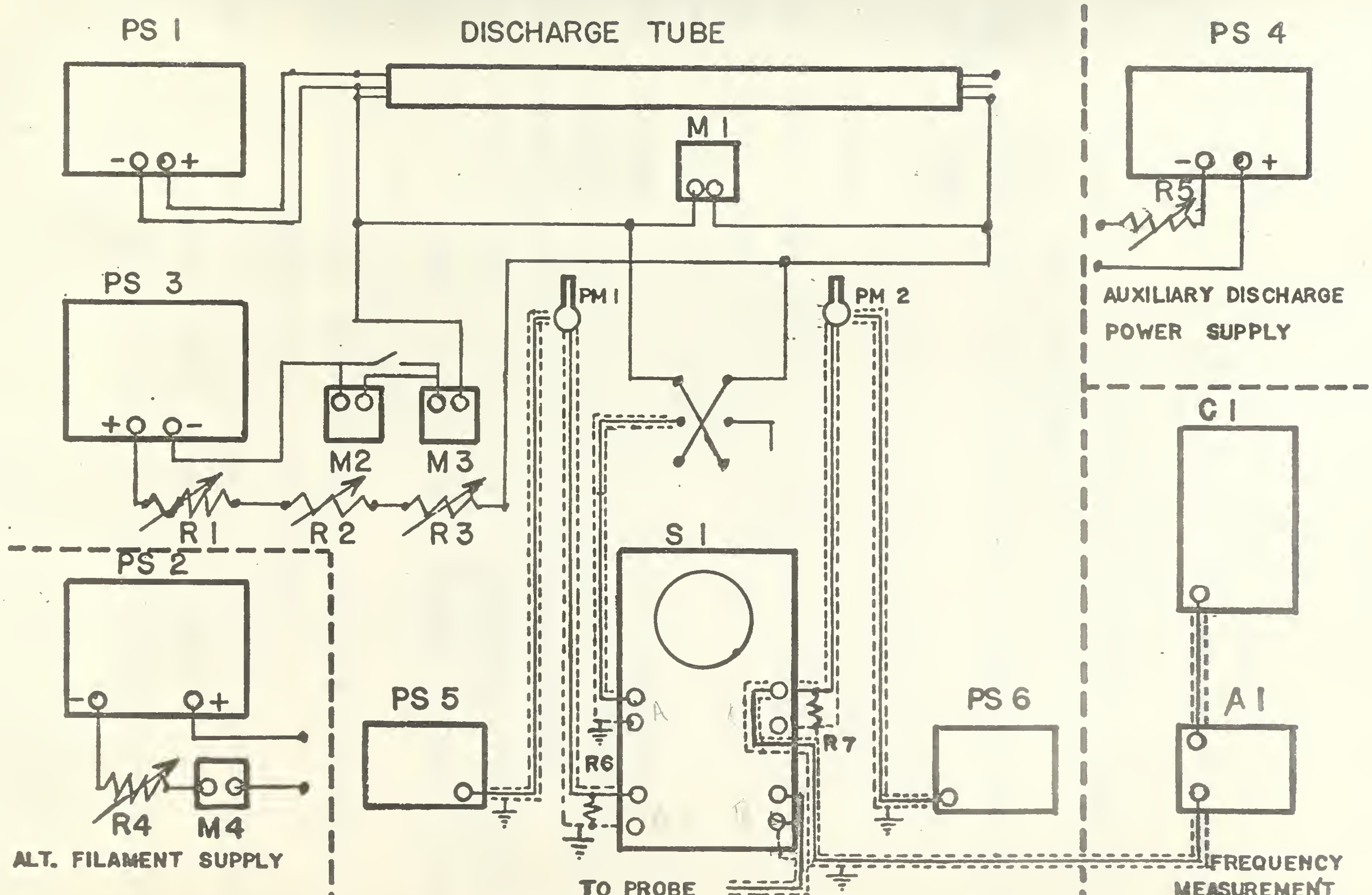


FIGURE 4 SCHEMATIC

List of Equipment in Figure 4.

PS-1 Kepco Model KM 236-15A Filament Power Supply; 0-15a, 0-35v with ammeter and voltmeter.

PS-2 Batteries for alternate filament supply-48 volts.

PS-3 Kepco Model 770 B main discharge power supply; 0-2.25a, 0-600v.

PS-4 Sorenson Model 1000 BB Auxiliary Discharge Power Supply, 0-500ma, 200-1000v.

PS-5 and PS-6 Locally constructed Photomultiplier Power Supply; 0-25ma, 0-1500v.

M-1 Hewlett Packard Model 410 B Vacuum Tube Voltmeter, 0-1000v.

M-2 Weston Model 322 Ammeter; 0-20, and 0-200 ma.

M-3 Weston Type PX-5 Ammeter, 0-2.0 amp.

M-4 Simpson Ammeter, 0-15 amp.

S-1 Tektronix, Type 551 A, Dual Beam Oscilloscope.

A-1 Hewlett Packard Model 450 A Amplifier, 20 and 40 db gain.

C-1 Hewlett Packard Model 521 A Electronic Counter.

R-1 Eight 200 ohm, 1 amp, resistors connected with four in series on each of two parallel branches to give 0-400 ohm, with 2 amp capacity.

R-2 Two 890 ohm, 1 amp, slide wire resistors in series to give 0-1780 ohm with 1 amp capacity.

R-3 Ten ceramic resistors from 1 k-ohm to 20 k-ohm connected to give 0-65 k-ohm in steps of 1 k-ohm.

R-4 Ceramic resistor 0-50 ohm 10 amp to control current to filaments.

R-5 5700 ohm 270 ma slide wire resistor to control auxiliary discharge current.

R-6 and R-7 100 k-ohm Tubular resistor for photomultiplier input to oscilloscope.

PM-1 and PM-2 RCA 1P21 Photomultiplier Tube.

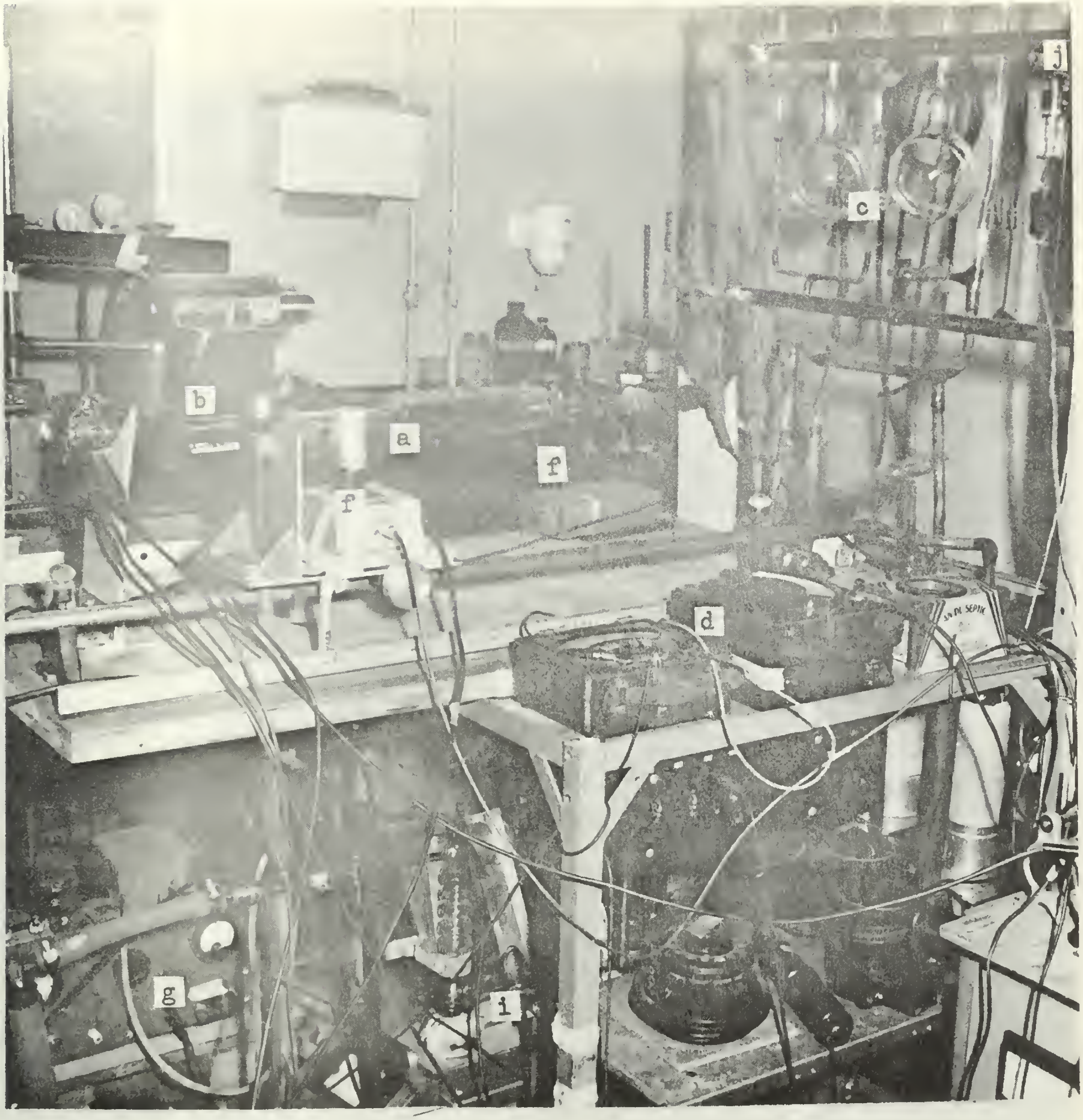


Figure 5 - General View of Discharge Tube and Vacuum System

a. Discharge Tube
b. Rotating Mirror
c. Gas Bottles
d. Ammeters
e. Liquid Air Traps
f. Photomultiplier
g. PS-6
h. R-3
i. Diffusion Pump
j. Ion Gauge

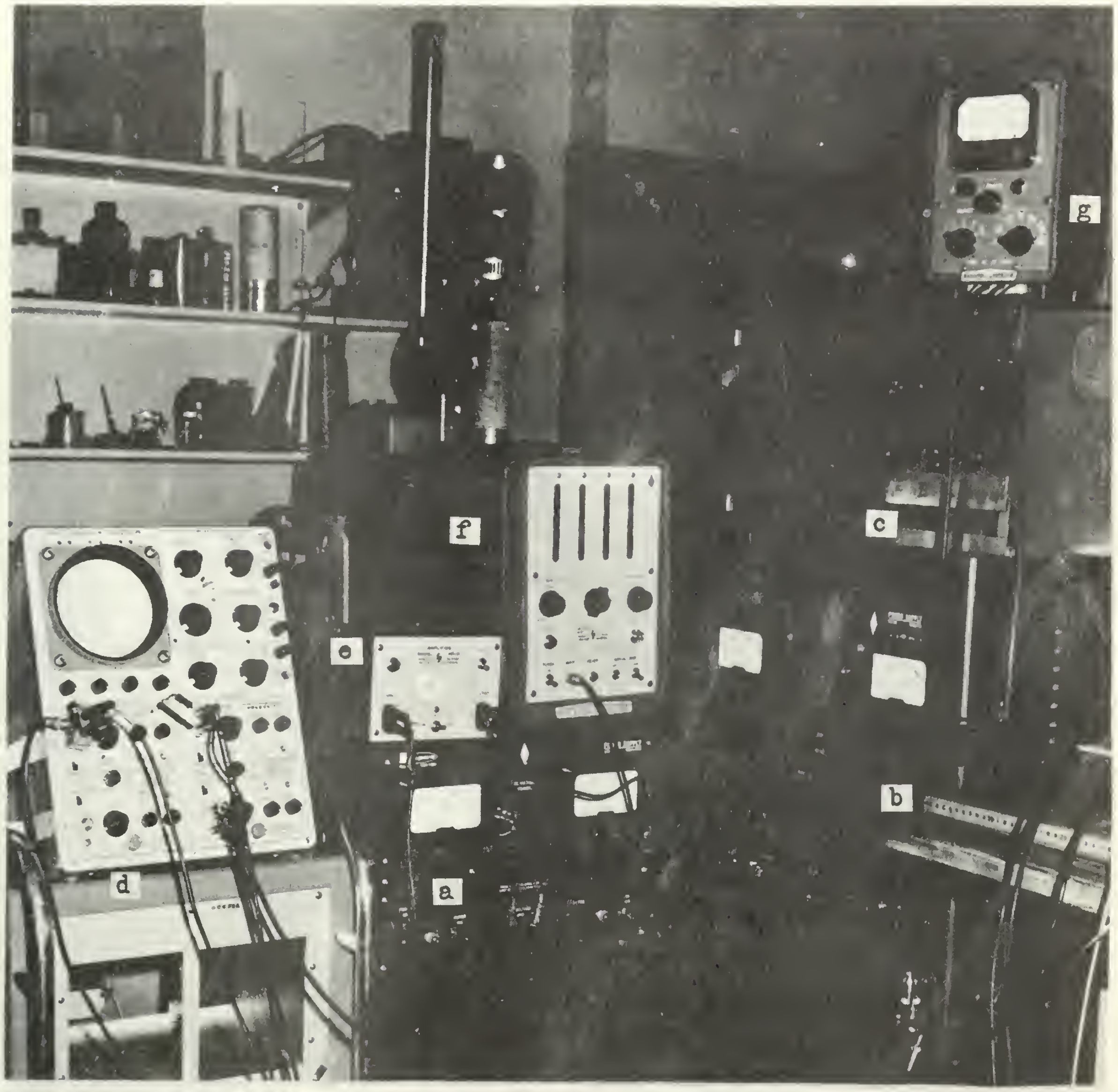


Figure 6 - Electronic Equipment

a. PS-1
b. PS-3
c. R-1
d. Dual-Beam Oscilloscope
e. Decade Amplifier
f. Frequency Counter
g. Volt Meter

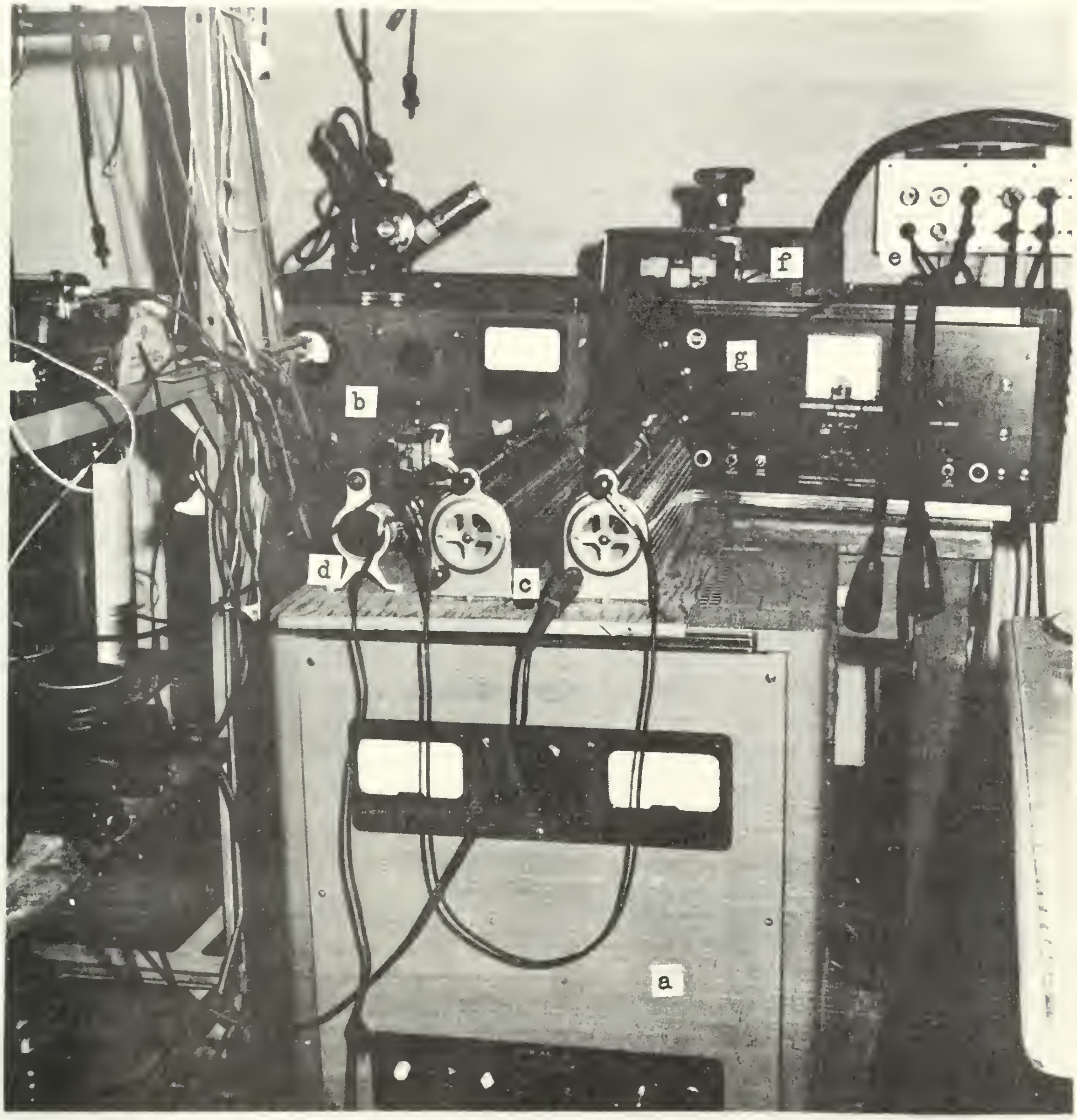


Figure 7 - Electronic Equipment

a. PS-4
b. PS-5
c. R-2
d. R-5
e. PS-2
f. R-4
g. Ion Gauge

DISCHARGE TUBES

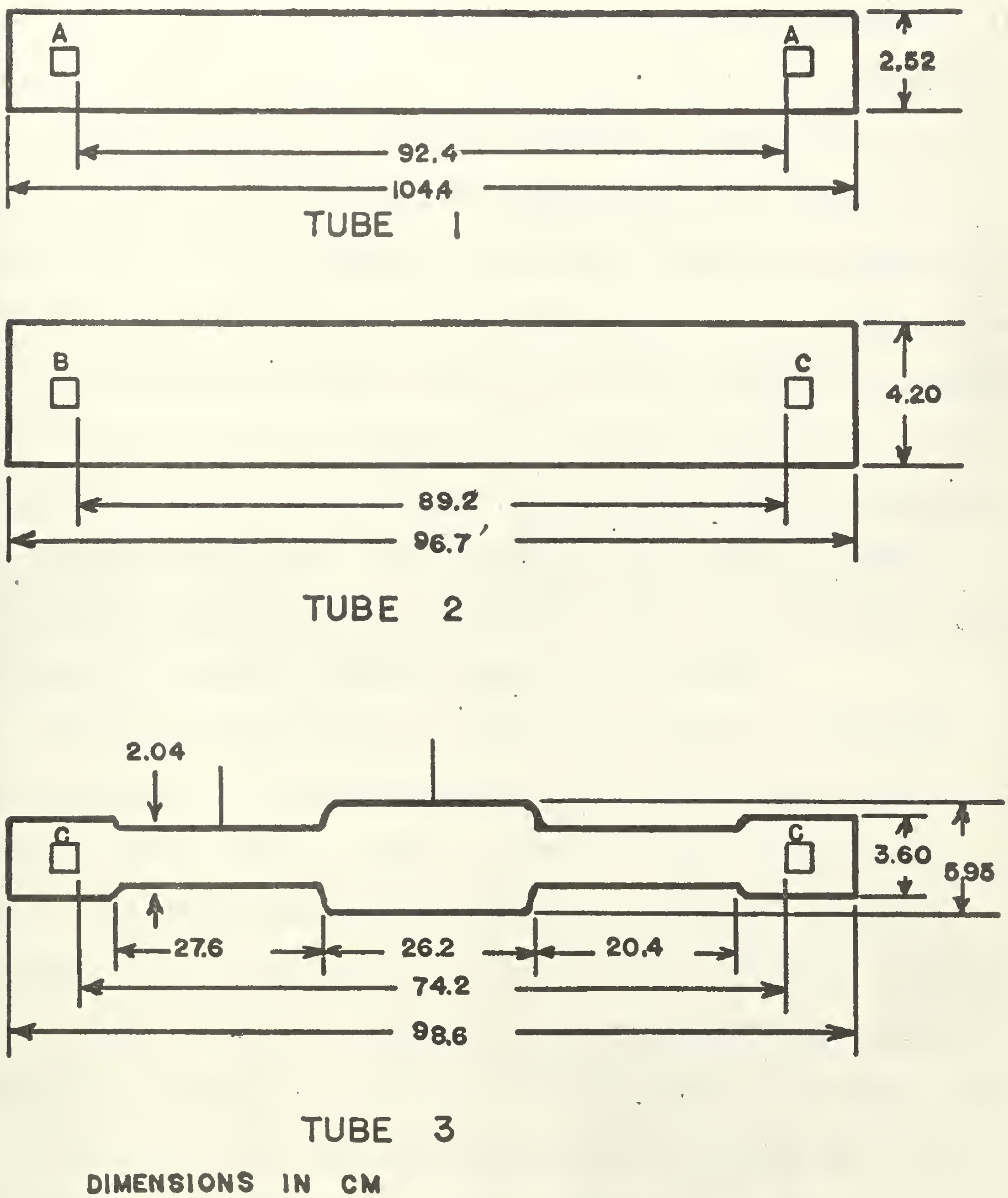


FIGURE 8

2.4 Pupp's Anode Operation.

Since one of the major objectives of this work is to establish the role of the oscillating anode fall region (anode spots) in an inert gas discharge and to determine the correlation between the anode spots and the phenomenon of moving striations, it was necessary to have a means by which the anode spots could be controlled or, preferably, eliminated. It was decided to use the technique reported by Pupp (5), by which an auxiliary discharge is produced in the anode fall region itself. This auxiliary discharge produces a high concentration of positive ions and electrons in the anode fall region that eliminates the oscillations by allowing the positive column to extend to the anode surface.* It was decided that all tubes would be constructed so that this auxiliary discharge could be used when desired.

It would be desirable to devise a means of electrode construction that would allow the electrode to be used as the cathode (either hot or cold cathode) as well as the Pupp's anode. The first electrode design (see type A, figure 9) consisted of a 2 cm diameter, 2.5 cm long, cylinder rolled from a sheet of 10 mil nickel. The filaments consisted of two circular coils of 9.6 mil, 41 mil mandrel, 53 turns per inch, tungsten wire concentric with the cylinder axis and centered longitudinally on the cylinder axis. The two halves of each circular coil connected in parallel and the two

*Pupp used a low voltage (approximately 30 volts) and a high current (1 amp or more) in his work with an auxiliary discharge at the anode. The authors obtained similar results with a high voltage (100 volts or more) and low current (60 ma or less)

ELECTRODE TYPES

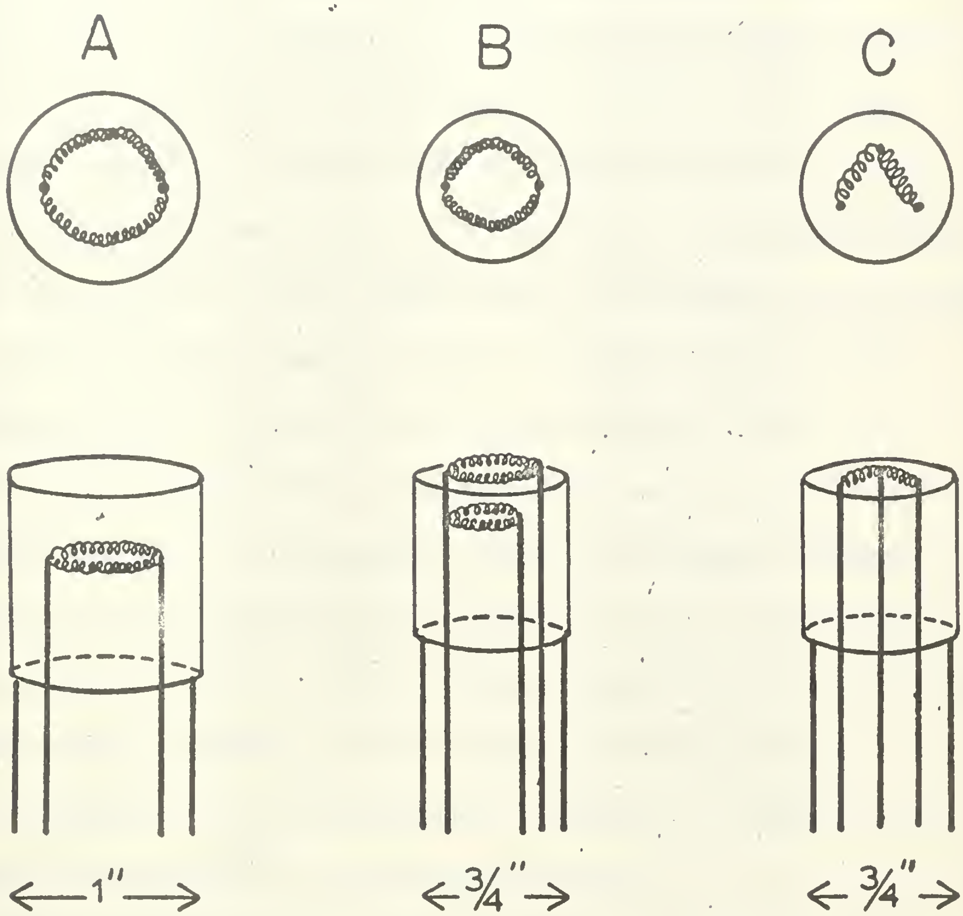


FIGURE 9

coils could be connected in series. Because of the short life expectancy of the tungsten filaments due to ion bombardment, this circuit gave the advantage of having effectively four independent filaments; any one of which could be operated after one or more of the others had burned out. With all sections of the filaments in operating condition, one full coil was normally operated at a current of 8 amps (four amps passing through each half of the coil). This design had been shown to be satisfactory in cathode operation by A W Cooper in his experiments performed the previous year. Glass pinches used in the electrode construction were obtained from burned out VG1A ion gauge tubes.

It was believed that this design could also be used for the Pupp's anode. A discharge could be started between the filaments and the surrounding cylinder with a high voltage applied across the two. The cylinder would be the anode for both the main discharge and the auxiliary discharge. However, in operation, the auxiliary discharge failed to have any significant effect on the anode spots.

It was suspected that the auxiliary discharge, being well inside the cylinder, did not provide the high ion concentration at the end of the cylinder where it was needed. The electrode design was modified by reducing the cylinder length to 1.2 cm and placing the first coil of the filament right at the end of the cylinder. The auxiliary discharge would now be between the filament and the portion of the anode at which the anode spots were located. This modification was successful. An auxiliary discharge current of

approximately 60 ma was sufficient to eliminate the oscillating anode spots and allow the positive column to extend to the anode. The Pupp's anode was equally effective with the anode filament either hot or cold. Measurements were made with the Pupp's anode operating cold cathode because then the anode spots could be monitored with a photomultiplier tube to insure that they were being extinguished. Having proved successful in operation, the electrode design provided an extremely flexible arrangement for the experiments. Being able to use either end of the tube as the anode enabled us to obtain the same data from the tube number 3 (which has a probe in only one of the smaller end sections) that would be obtained if there were probes in each smaller end section. This was accomplished by reversing the anode and cathode.

One additional modification was made in electrode design. It was found that two 14 mil coiled tungsten filaments operated in series, at 8 amps; and placed in the ends of the cylinders, provided a much longer lifetime while providing the necessary emission of electrons.

2.5 <u>Frequency Measurement Procedures</u>.

In the measurement of moving striation frequencies, the cathode filament current was maintained at a constant value throughout the series of measurements. The frequency was measured while steadily increasing the discharge current from the lowest value desired, or obtainable, to the current for extinction of striations.

The first method used for measurement of the striation

frequency involved the use of one photomultiplier tube and the oscilloscope. The photomultiplier output was displayed on the oscilloscope, with a calibrated sweep, and a photograph taken of the trace. The period of the striation oscillation was read directly from the photograph and the frequency thus computed. (See figure 10).

In the second method of frequency measurement, the photomultiplier output was placed across the 150 k-ohm resistor and to a decade amplifier providing a 20 db gain. The amplifier output was connected to a frequency counter which counted the frequency of the striations directly. This method was much more suitable for frequency measurement as a series of readings could readily be taken at the same current and a statistical error determined. With the frequency counter, ten one-second counts were made at each current providing accuracy of the order of 1% or better on the frequency measurements. By comparison of the frequency counter data with the direct frequency measurement discussed above, the accuracy of the earlier frequency data was estimated to be of the order of 5%.

During the frequency measurements, the photomultiplier was fixed at a point along the discharge tube and was not moved during the series of measurements. In tubes 1 and 2 this was not of particular importance as little dependence of frequency upon position along the tube was observed; providing the photomultiplier was a few cm from the electrodes. In tube 3 the photomultiplier also was kept well away from the tube radius transitions and the probes to eliminate, as much

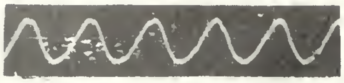


Figure 10 - Photomultiplier Trace for Frequency Measurement

T = 0.5 msec/cm
f = 1065 cps

Figure 11 - Rotating Mirror Photograph for Wavelength Measurement

Distance between markers: 10cm and 5 cm
λ = 3.8 cm

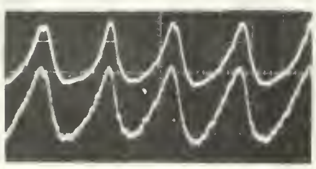


Figure 12 - Oscilloscope Photograph of Two Photomultiplier Traces In Phase

as possible, any effects upon the frequency.

2.6 Wavelength Measurements.

The distance between striations, hereafter referred to as wavelength, was measured in conjunction with the frequency measurements for both tubes 1 and 2. In general, the wavelength measurements were not taken as frequently as the frequency measurements.

In tube 1, all wavelengths were measured from rotating mirror photographs as shown in figure 11. The photograph was projected with an opaque projector to provide magnification of approximately 10 times; the wavelengths then being measured directly. A photograph of the rotating mirror is shown as figure 13.

In tube 2, the rotating mirror photographs were also used, but a second photomultiplier was used with the output connected to another channel of the oscilloscope. The two photomultipliers were placed at the same point along the discharge tube with one on either side of the tube. This point could be accurately determined by observing when the traces on the oscilloscope were in phase. (Figure 12)

The second photomultiplier was then moved along the tube until the two traces were again in phase and the wavelength was measured directly from the separation of the two photomultipliers. The measurement of wavelength by this method was limited to conditions where a stable striation wave form was present. When we did not have stability, the wavelength was measured from rotating mirror photographs.

The accuracy of the wavelengths measured by the two

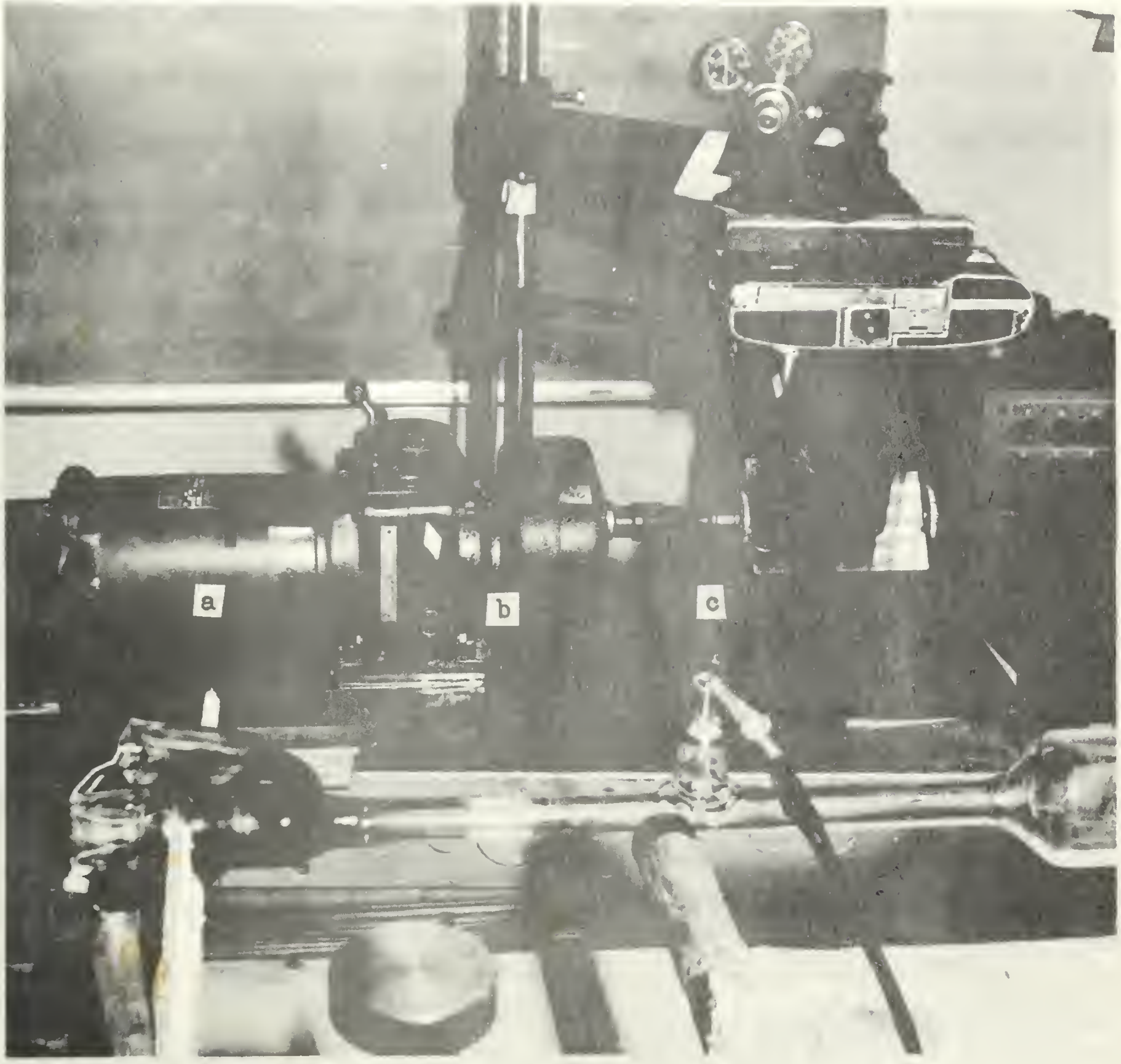


Figure 13 - Rotating Mirror

a. Electric Motor - Marathon Electric, Mod. VE, ¼ HP continuous duty, 3 Ph.- 220/440 volts.

b. Graham Variable Speed Transmission - 3450 RPM input; 0 to 9250 RPM output.

c. Mirror - 4" X 6" X 1" Solid Stainless Steel with evaporated Aluminum on Polished Surface.

photomultiplier method was of the order of 0.5 cm at the longer wavelengths and 0.1 cm at shorter wavelengths. Comparison with the wavelengths measured by the rotating mirror photographs provided an estimated error on the measurements by the rotating mirror of 5 to 10%.

3. OBSERVATIONS AND ANALYSIS OF STRIATION PARAMETERS

3.1 Frequency.

The frequency of moving striations in a positive column was measured in the four different tube radii used over a range of currents from approximately 200ma to extinction of striations in Tube # 1; from the lowest current at which moving striations could be detected, and a discharge could be maintained, to cutoff in Tube # 2; and for four different currents in Tube # 3. In Tube # 1 the pressure was varied from 1.1 to 15.2 mm Hg, in Tube # 2 from 1.1 to 16 mm Hg, and in Tube # 3 from 0.37 to 14.2 mm Hg.

Frequency measurements in Tube # 1 were made entirely from pictures of photomultiplier traces upon the oscilloscope as described in Section 2.5. In Tubes # 2 & 3 frequencies were measured by use of the frequency counter, with the exception of the 1.9 mm Hg pressure in Tube #2, where the oscilloscope photographs were used.

In all tubes the frequency measurements were made while steadily increasing the current from the lowest current to the highest current. In Tube #2, after completion of the run to cutoff current, checks were made at lower currents to determine reproducibility of the results. Frequency was measured throughout the current range, at various current intervals disregarding the relative stability of the photomultiplier trace on the oscilloscope.

The accuracy of the frequencies measured by the oscilloscope photographs is estimated to be of the order of 50 cps or 5%, whichever is greater. Standard deviations of the

mean are shown for frequencies, measured with the frequency counter, in Figures 19 & 32; these deviations are representative of the accuracy for the other frequency counter measurements.

Figures 14 and 15 summarize the frequency observations as a function of pressure and tube radius at two different currents. The frequency of the striations varies inversely with the tube radius. The frequency of the striations is very high at low pressures (less than 1 mm Hg), decreases with increasing pressure to a minimum value between 3 and 6 mm, which is dependent upon the tube radius and may be dependent upon the tube current. The frequency of the striations then increases steadily with increasing pressure.

Figure 16 presents frequency as a function of pressure, for various tube currents, and a tube radius of 2.97 cm. Donahue and Dieke (7) show similar plots for currents from 4ma to 70ma in a tube of 0.75 cm radius. Their curves also exhibit a frequency minimum in the range of 6 to 8 mm pressure. These frequency minima also appear at the higher currents used here and tend to appear at lower pressure in the larger radius tube. In this large radius tube the striation frequency appears to decrease with increasing current, but this relation does not hold true when more detailed plots of frequency versus current are made.

Figures 17 and 18 present the frequency of the striations as a function of the discharge current for various pressures. The wide scatter of frequencies, and apparent peaks visible at higher pressures, in Figure 17, led to the

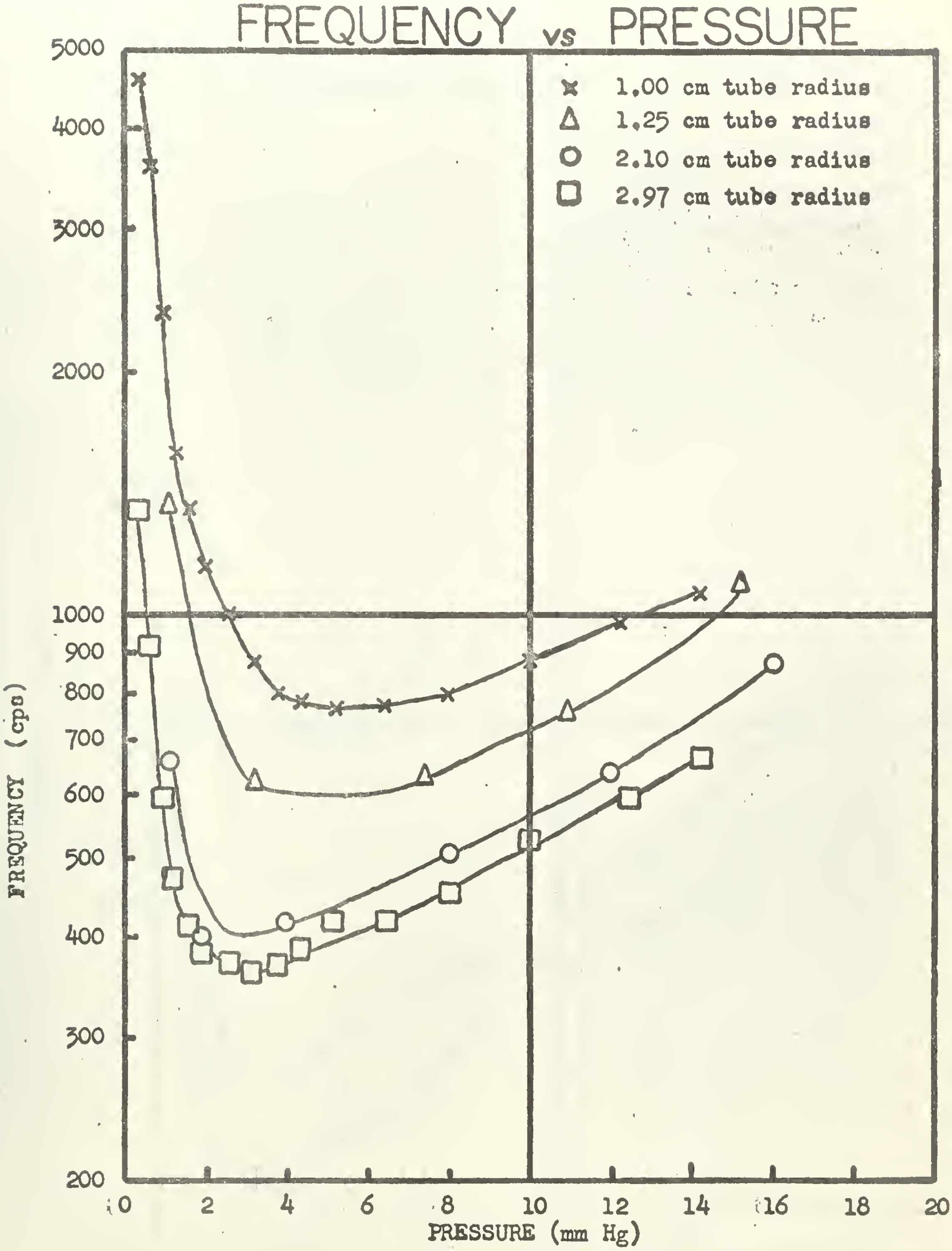


Figure 14

Argon, 240 ma Tube Current

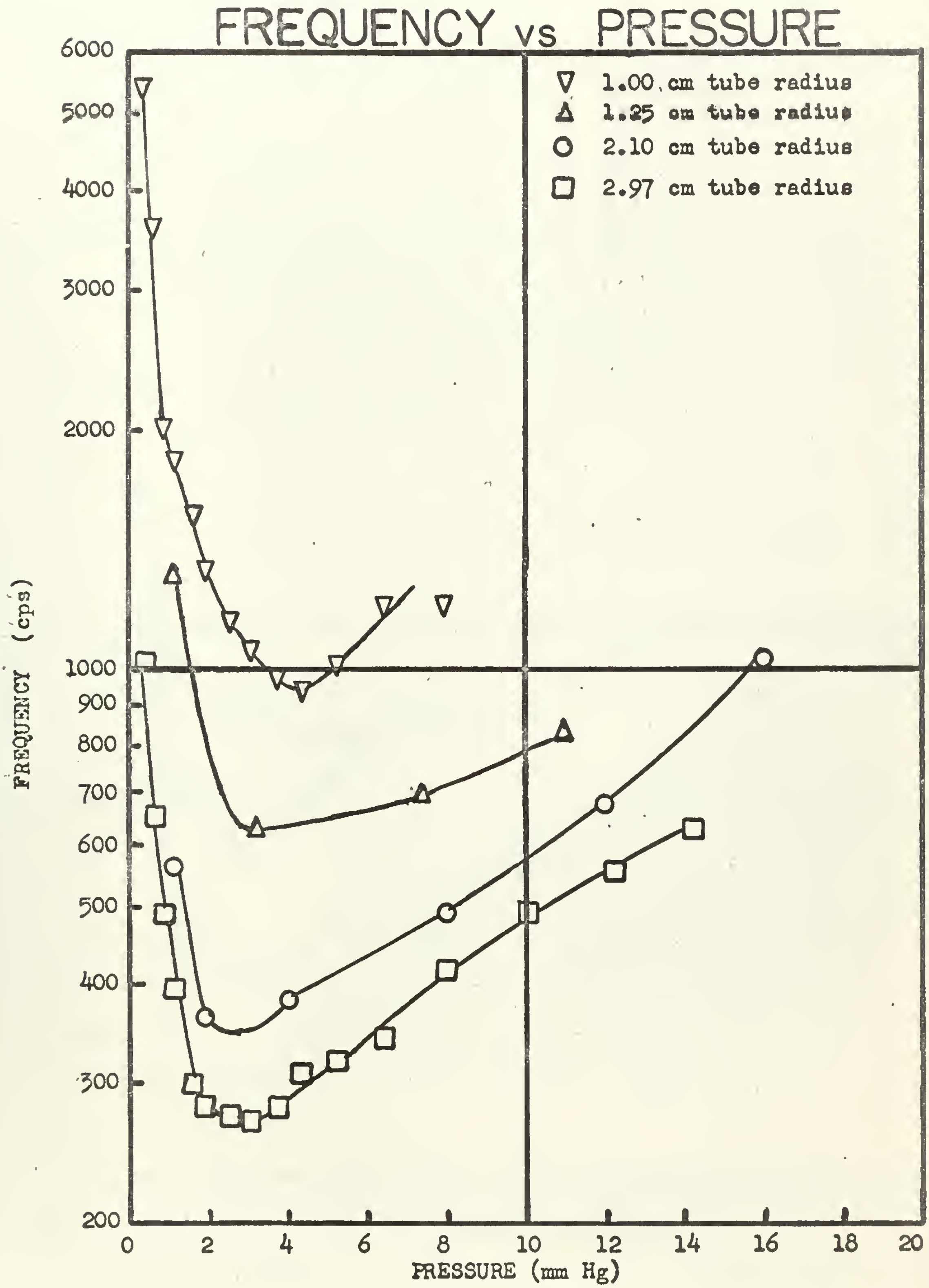


Figure 15

Argon, 500 ma Tube Current

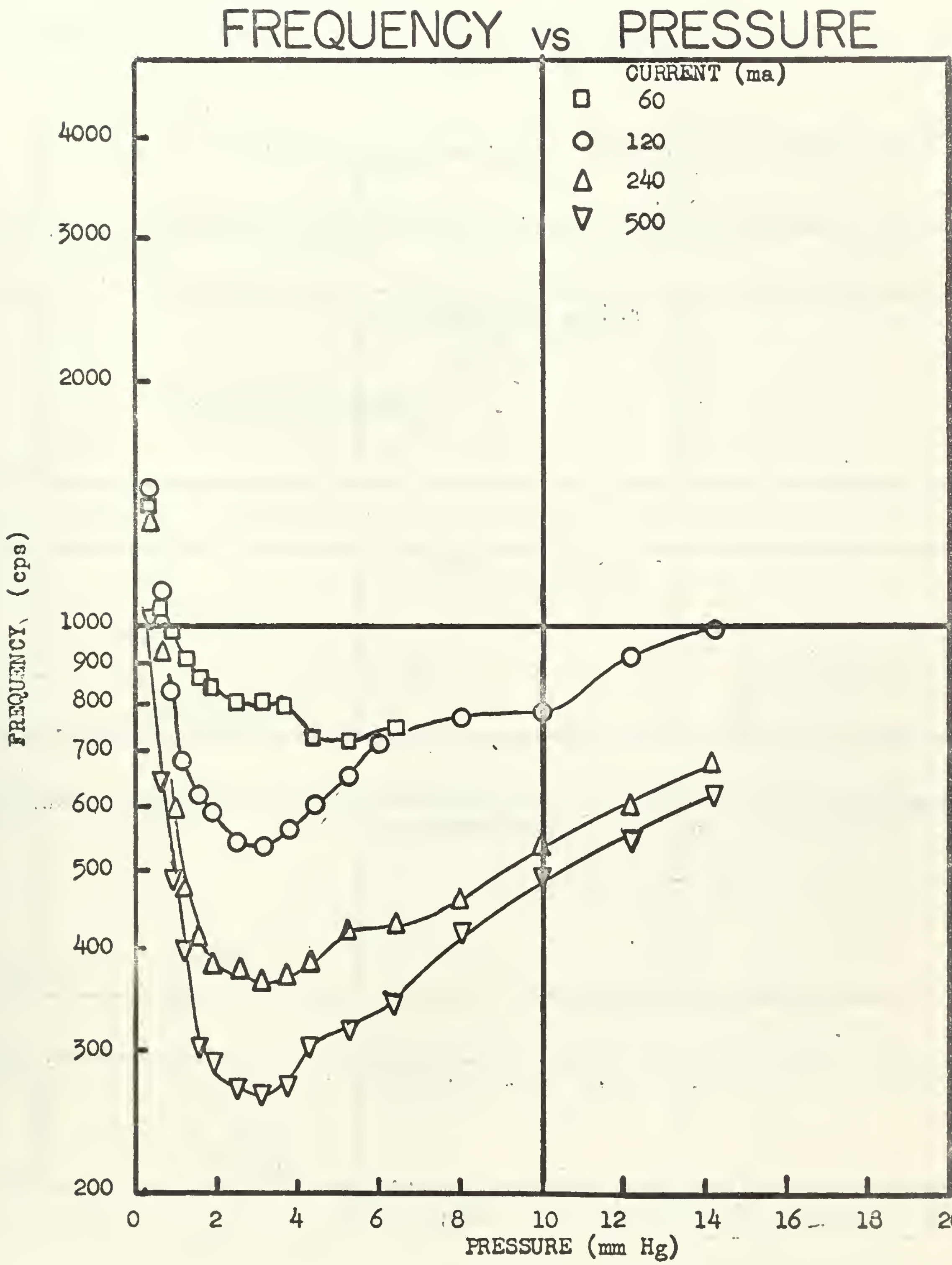


Figure 16

Argon, 2.97 cm Tube Radius

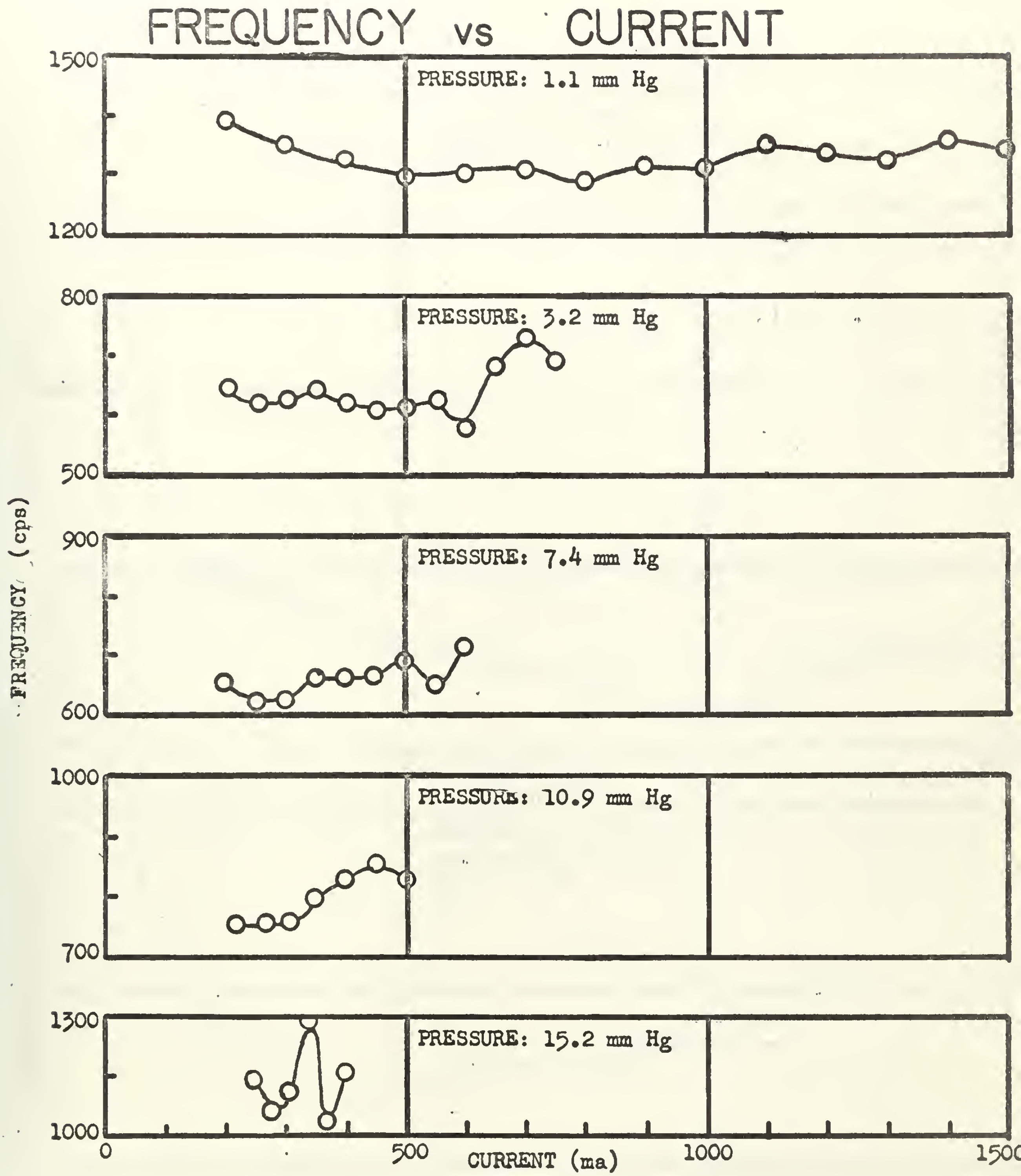


Figure 17

Argon, 1.25 cm Tube Radius

FREQUENCY vs CURRENT

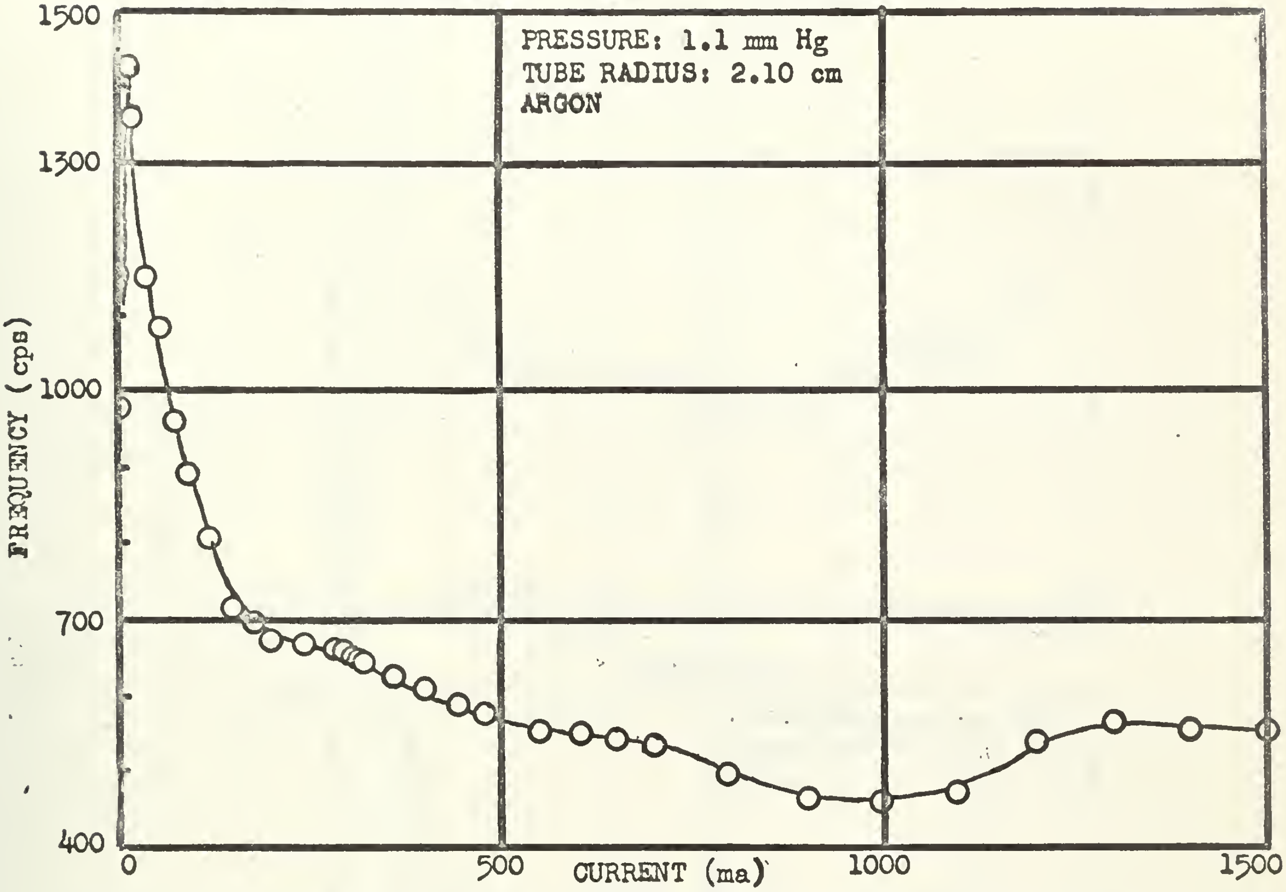


Figure 18a

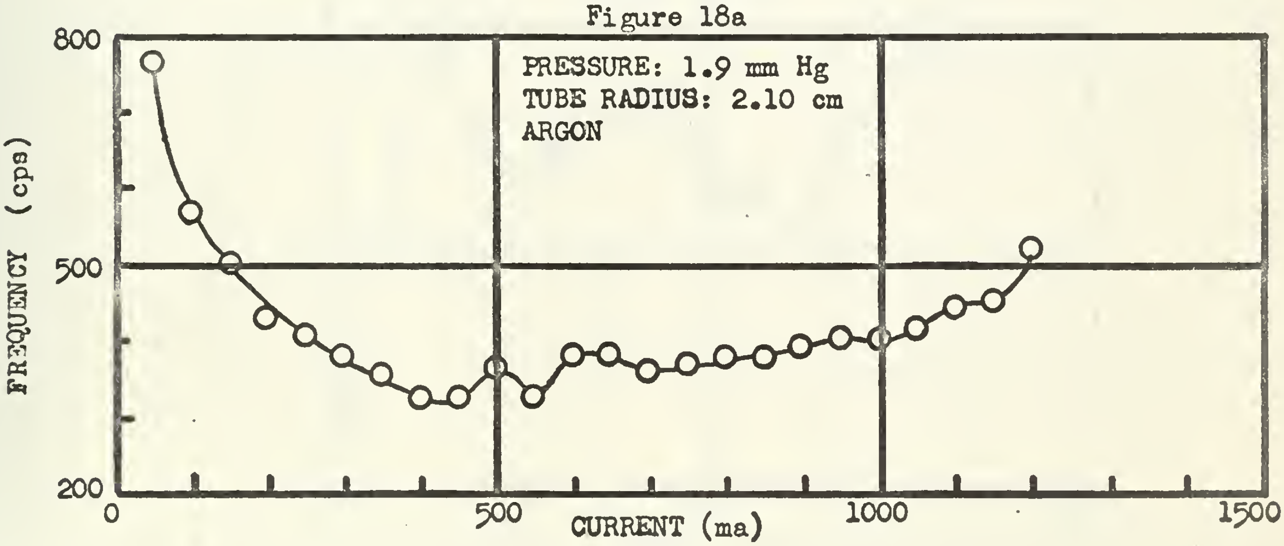


Figure 18b

FREQUENCY vs CURRENT

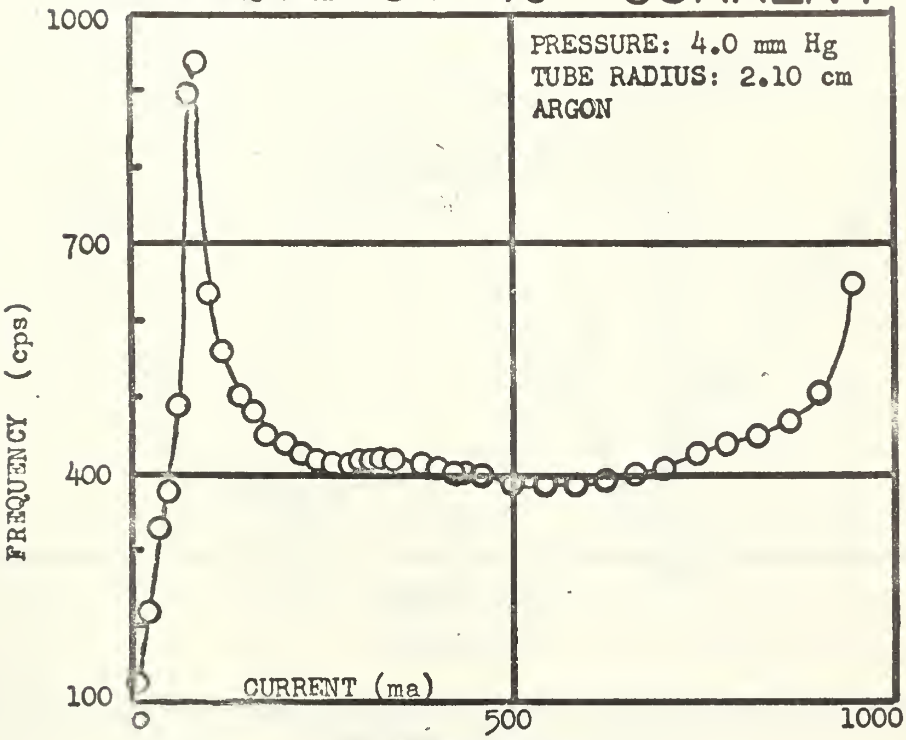


Figure 18c

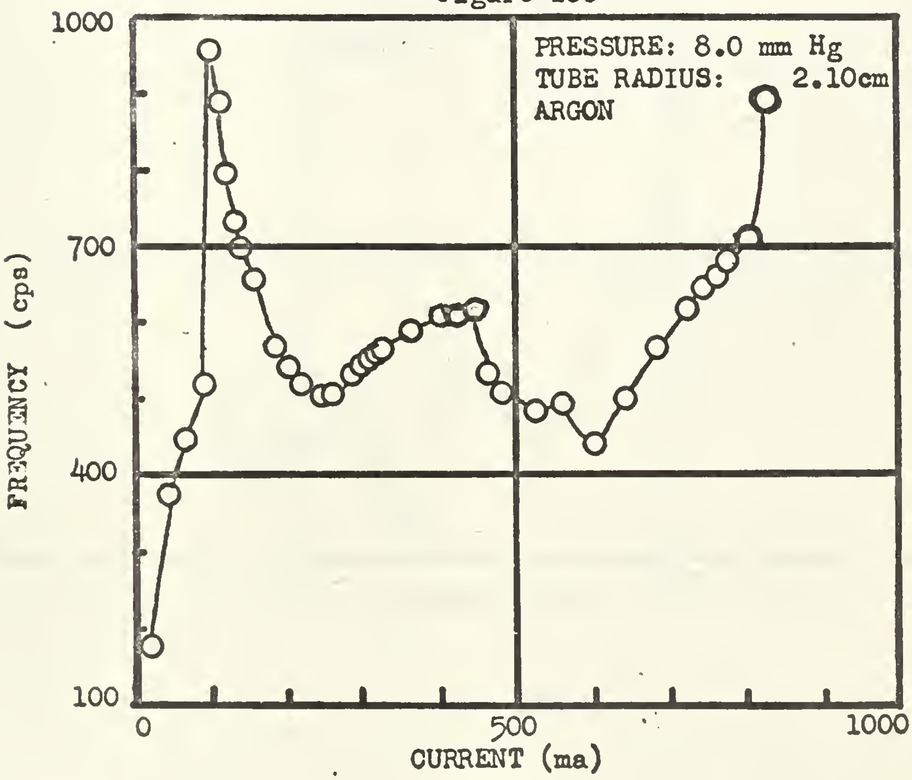


Figure 18d

FREQUENCY vs CURRENT

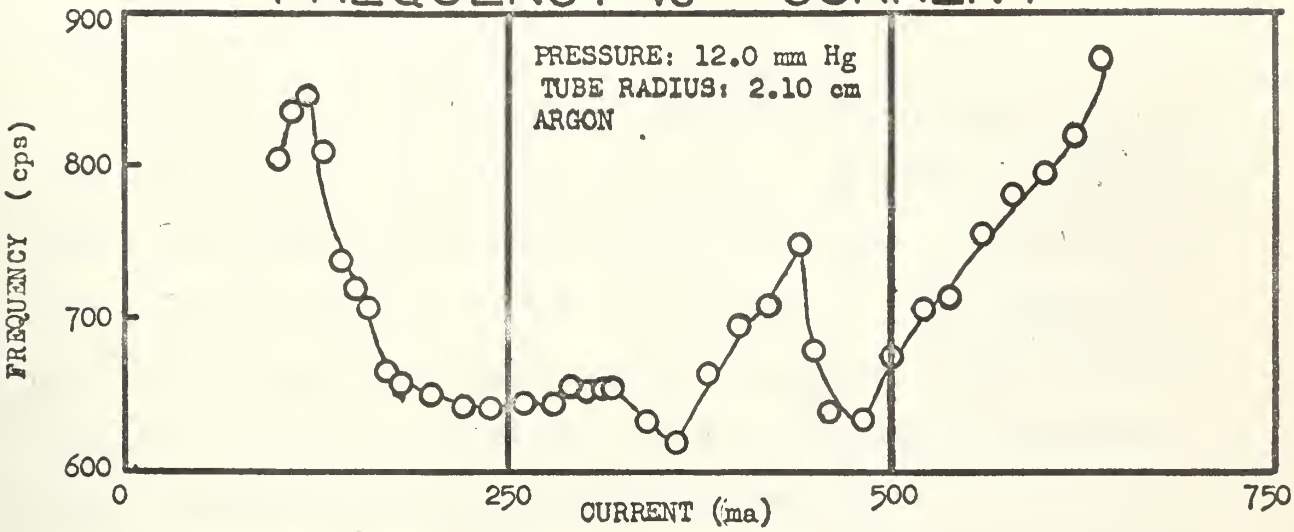


Figure 18e

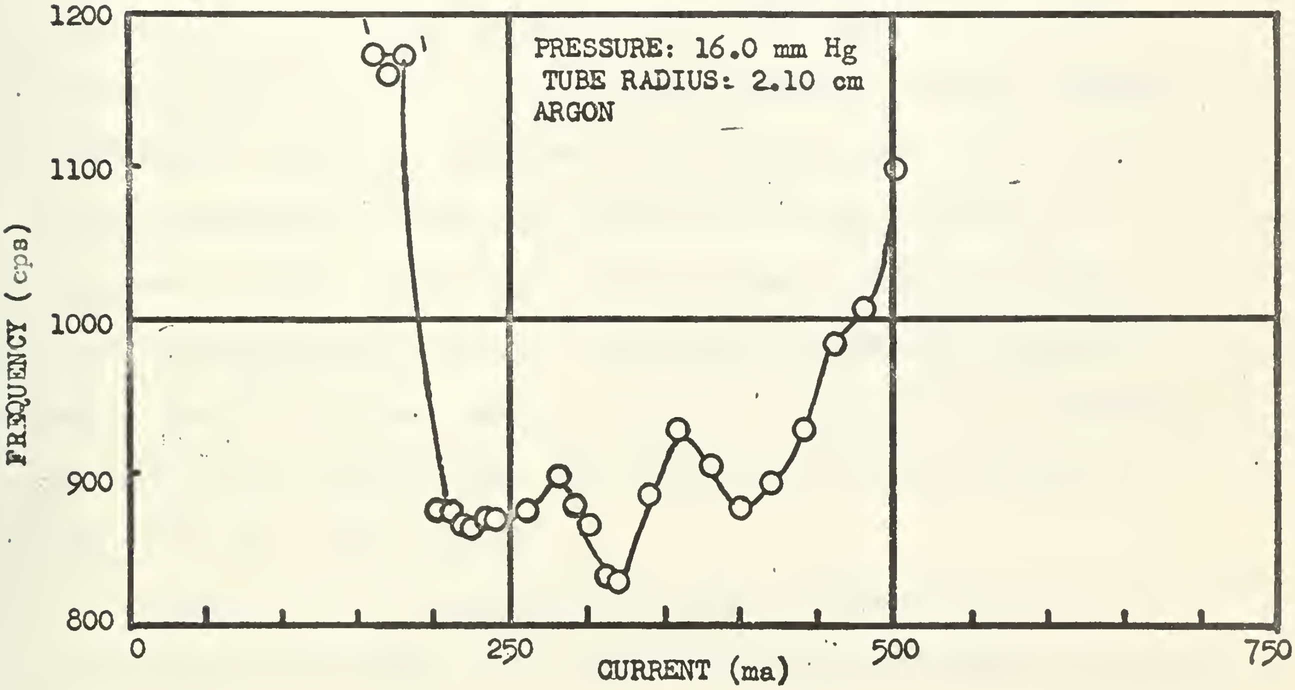


Figure 18f

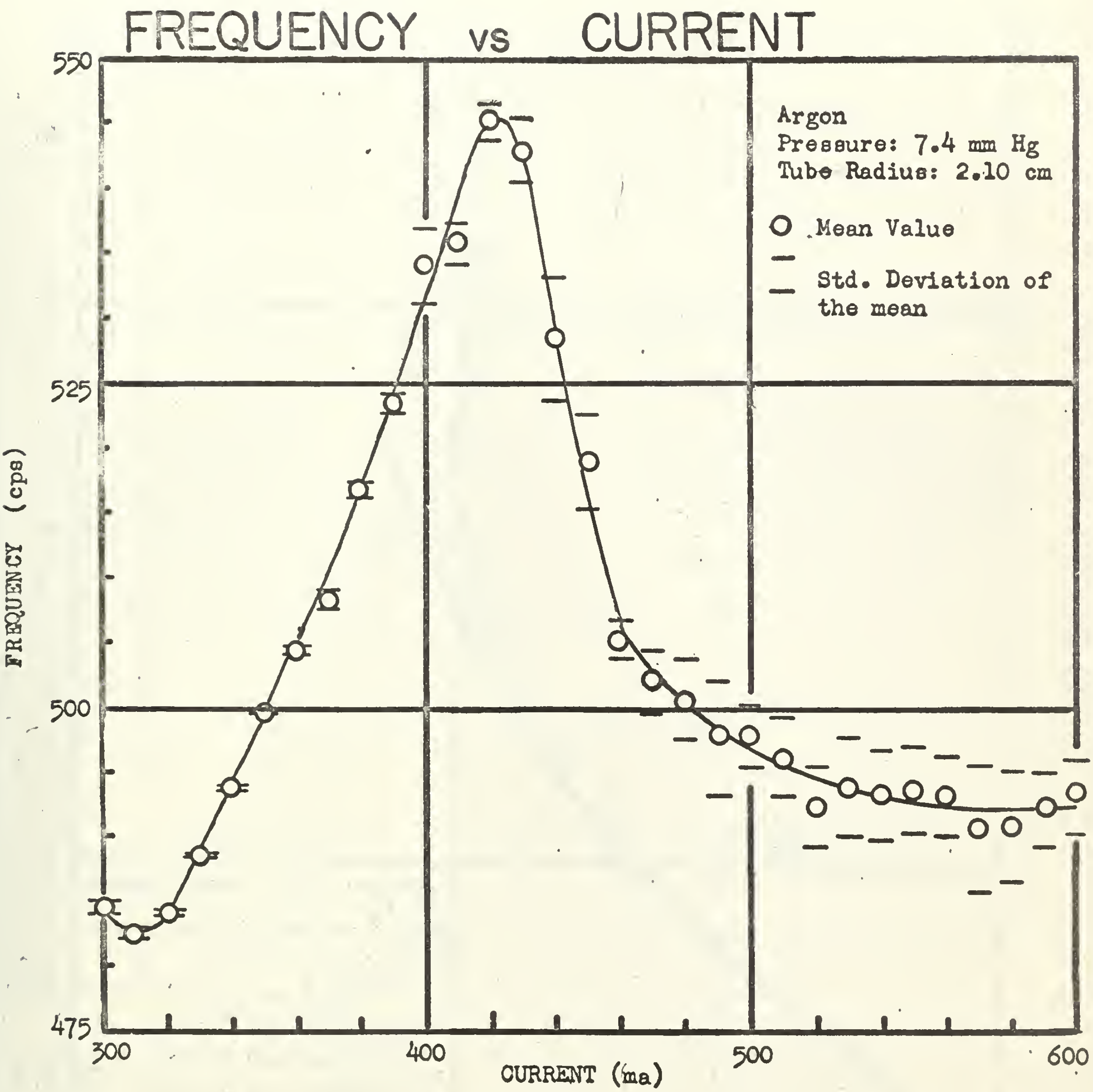
use of the frequency counter for frequencies plotted in Figure 18. *The pressures where the frequency counter was used show a continuous, although somewhat irregular variation of frequency with current.

To better demonstrate the frequency peaks shown at higher pressures in Figures 17 and 18, frequency measurements were made at discharge current intervals of 10 ma over the range from 300 ma to 600 ma in Tube #2. This data is plotted in Figure 19. The size of this peak is much greater than the largest standard deviation of the mean; therefore these frequency peaks are assumed to be real.

The variation of the frequency of the moving striations with current is quite complex. The frequency is at its maximum value at very low currents, generally where moving striations are first observed. The frequency falls rapidly with increasing current to a value of about one-half its maximum and then tends to a fairly stable level with further increases in current. At higher pressures, (8 mm or more) one or more secondary peaks of frequency are observed. As the current approaches cut-off value for any pressure the frequency again rises.

Figure 20 is a comparison of data reported by Pupp (4), and Donahue and Dieke (7), with frequency data obtained here. The parameters of tube radius times pressure versus tube radius times frequency were chosen by Pupp to demonstrate the validity of the similarity principle as applied to moving

*Frequencies measured at the 1.9mm pressure were not measured with the frequency counter.



FREQUENCY vs CURRENT
550
525
500
475
FREQUENCY (cps)
300
400
500
600
CURRENT (ma)
Argon
Pressure: 7.4 mm Hg
Tube Radius: 2.10 cm
Mean Value
Std. Deviation of the mean

Figure 19

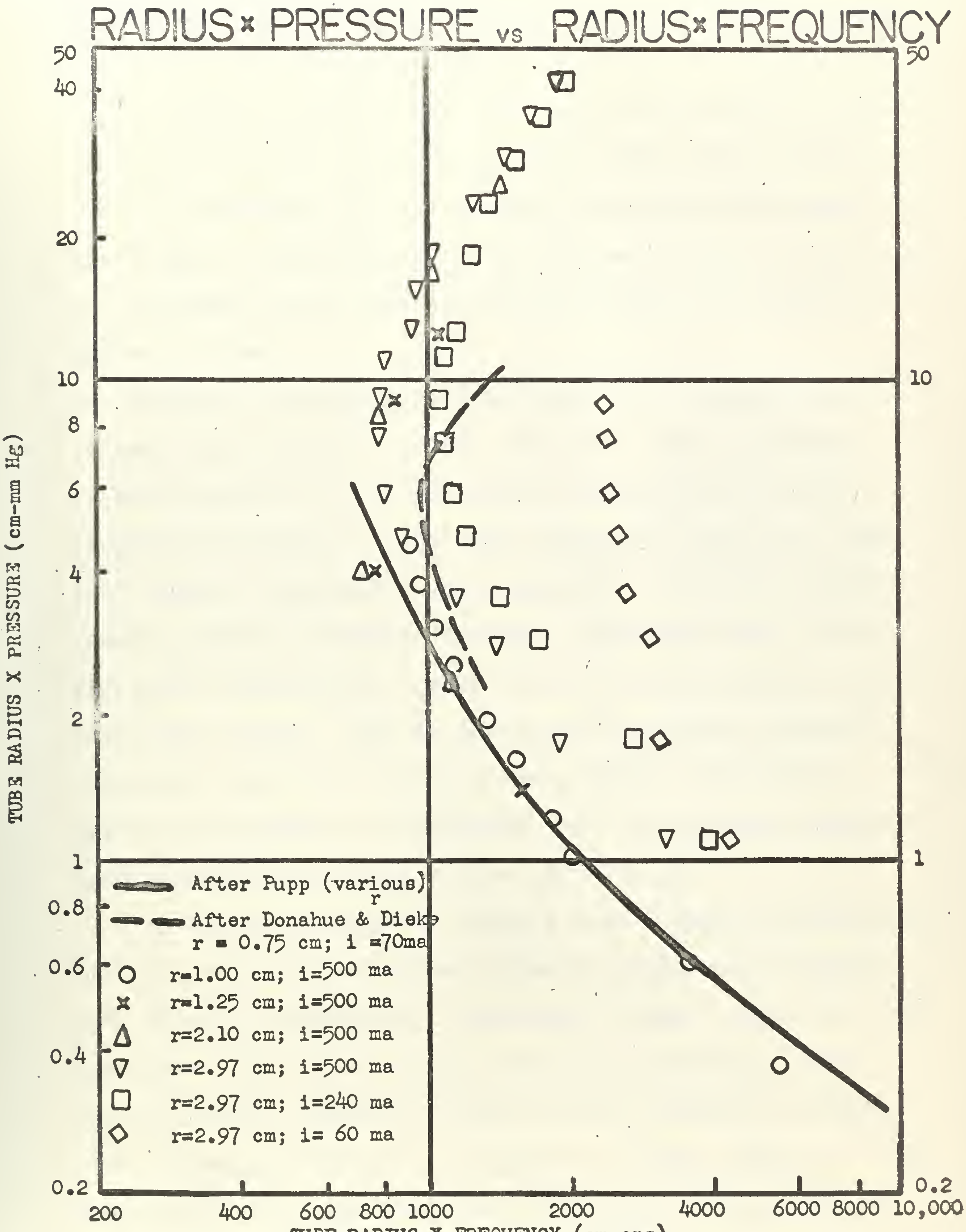


Figure 20
Argon

striations. The data from Donahue and Dieke were calculated from a plot of frequency versus pressure at a current of 70 ma in a tube of 0.75 cm radius. The data from Pupp's work represent a number of different tube radii and pressures, but the discharge currents at which the data were taken is not stated. From examination of Figures 1 and 2 of his work, it is assumed the discharge currents were of the order of 500 ma or more.

Francis (17) discusses the similarity principle as it is applicable to the positive column of a gas discharge. If the similarity principle holds for moving striations, products of pressure times tube radius and frequency times tube radius, and other similar parameter relations, should remain invariant between different discharge tubes. If the similarity principle is to be valid, certain physical processes are allowed, such as ionization by single electron collision, drift and diffusion of charges, and certain physical processes are forbidden, such as stepwise ionization and most collisions of the second kind.

As shown in Figure 20, Pupp's data support the validity of the similarity principle. However, Donahue and Dieke's data diverge considerably from Pupp's curve. Data from this experiment for 500 ma current and small pressure - tube radius products agree with Pupp's curve; however, considerably different curves are obtained at higher pressure - tube radius products. The data for 240 ma and 120 ma shows a large deviation even at the low pressure - tube radius product. There appears to be another convergence in the

data at high pressure - tube radius products for these lower currents

Although not conclusive, the data supports the similarity principle for low pressures, small tube radii, and high discharge currents. The divergence of these curves for high pressures, larger tube radii, and low discharge currents indicates that other physical processes, such as stepwise ionization, metastable state production and collisions of the second kind may be of importance.

3.2 Wavelength.

Wavelengths of the striations were measured by the two methods described in Section 2.6. For Figure 21 all wavelengths were measured by use of rotating mirror photographs, while for Figure 22, both rotating mirror and two photomultiplier methods were used.

Reproducible measurements with the two photomultiplier method were obtained within 0.5 cm, while the accuracy of the rotating mirror photograph method is poorer by at least a factor of two.

It is readily observed that the wavelength of the striations decreases quite rapidly with pressure for pressures less than 10 mm Hg. At pressures above approximately 10 mm Hg the decrease is much slower. Wavelength was observed to increase with increasing tube radius as shown previously by Pupp (4).

No indications of the wavelength changing in a "stepwise" fashion were noted here. Pupp, in Figure 1 of above referenced paper shows a step decrease in wavelength with

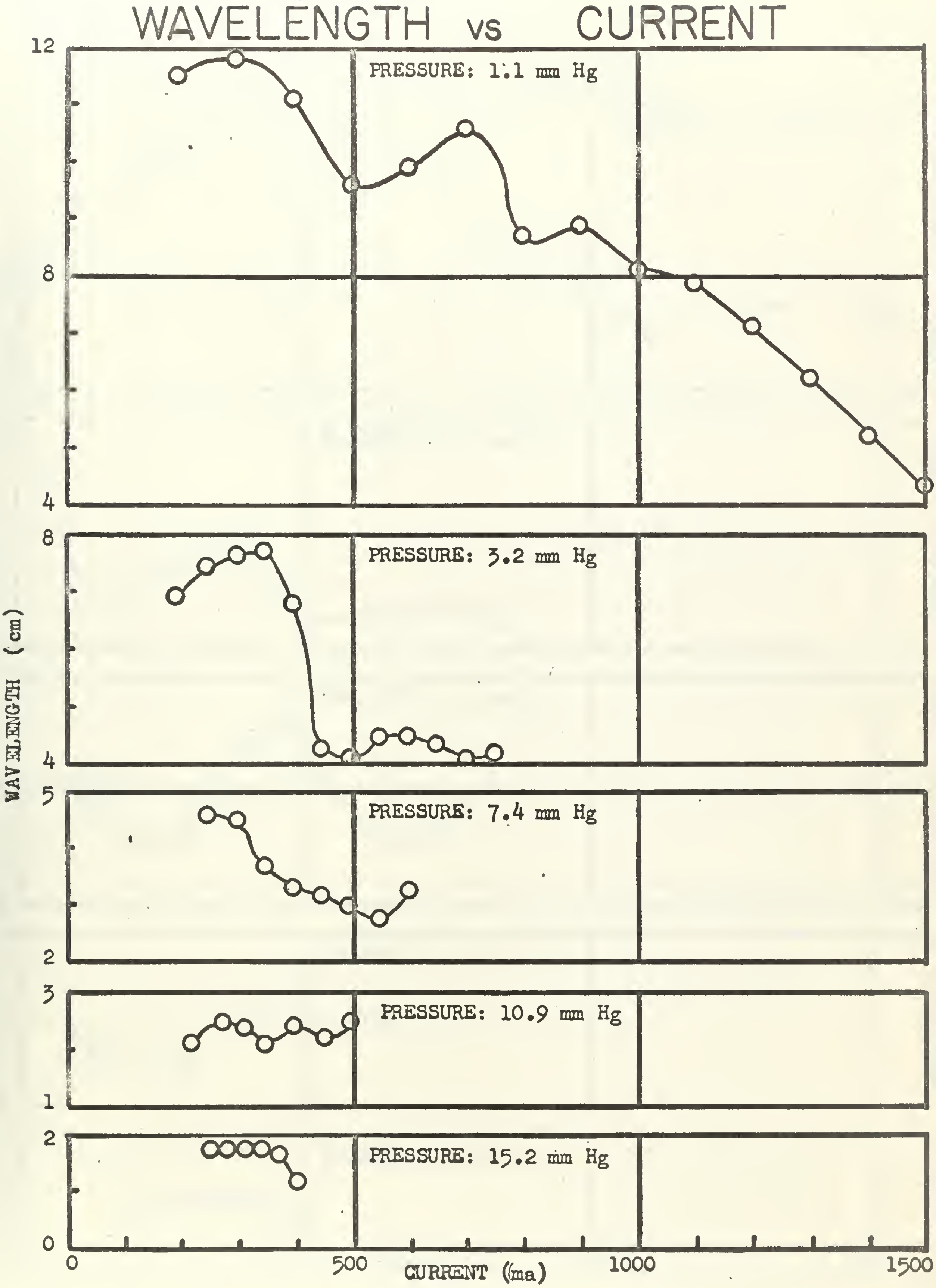


Figure 21
Argon, 1.25 cm Tube Radius

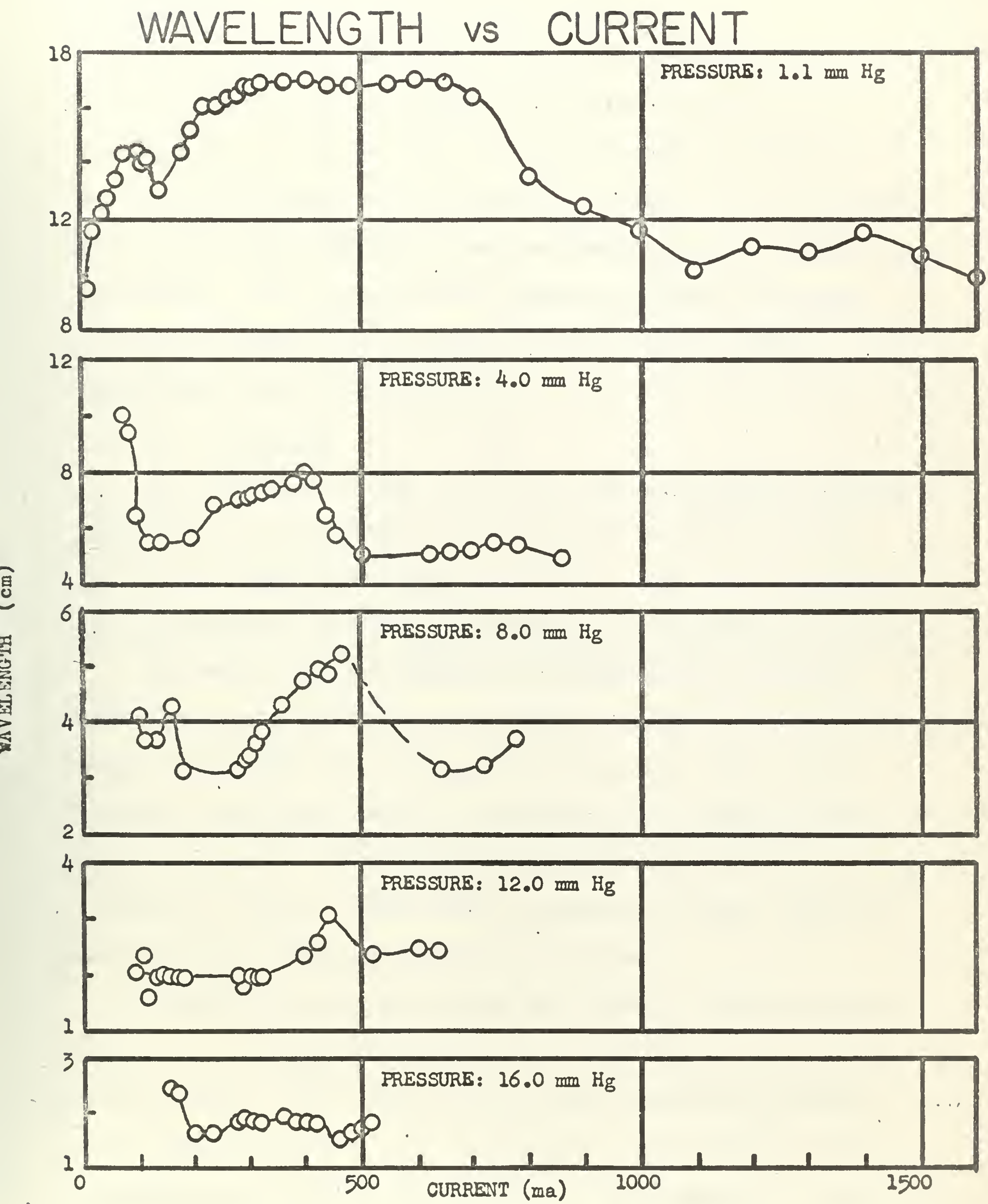


Figure 22
Argon, 2.10 cm Tube Radius

increasing current based upon maintaining an integral number of waves in the positive column.

In the measurements of wavelength here, the wavelength is a reasonably smooth function of current at a pressure of 1.1 mm Hg, but at higher pressures behaves in an irregular manner with increasing current. At the higher pressures, peaks appear in the wavelength as the current is increased. No connection was observed between the peaks of the frequency versus current curves and the peaks in the wavelength versus current curves.

3.3 Velocity.

The velocity of the striations was calculated from the product of the frequency and wavelength at each pressure and current where both were measured. Velocity is plotted as a function of current and pressure in Figures 23 and 24.

The velocity was observed to decrease quite rapidly with increasing pressure up to about 5 mm pressure and then much more slowly with increasing pressure. The velocity tended to decrease with increasing current, although at pressures greater than 1.1 mm the velocity behaved in a very irregular fashion. Tube radius appeared to have little effect upon the velocity of the striations.

Figure 25 shows four plots of velocity versus pressure made in an attempt to determine the dependence of velocity upon pressure. The velocity has been previously reported to be proportional to the reciprocal of the pressure and to the reciprocal of the square root of the pressure. (Section 1.4)

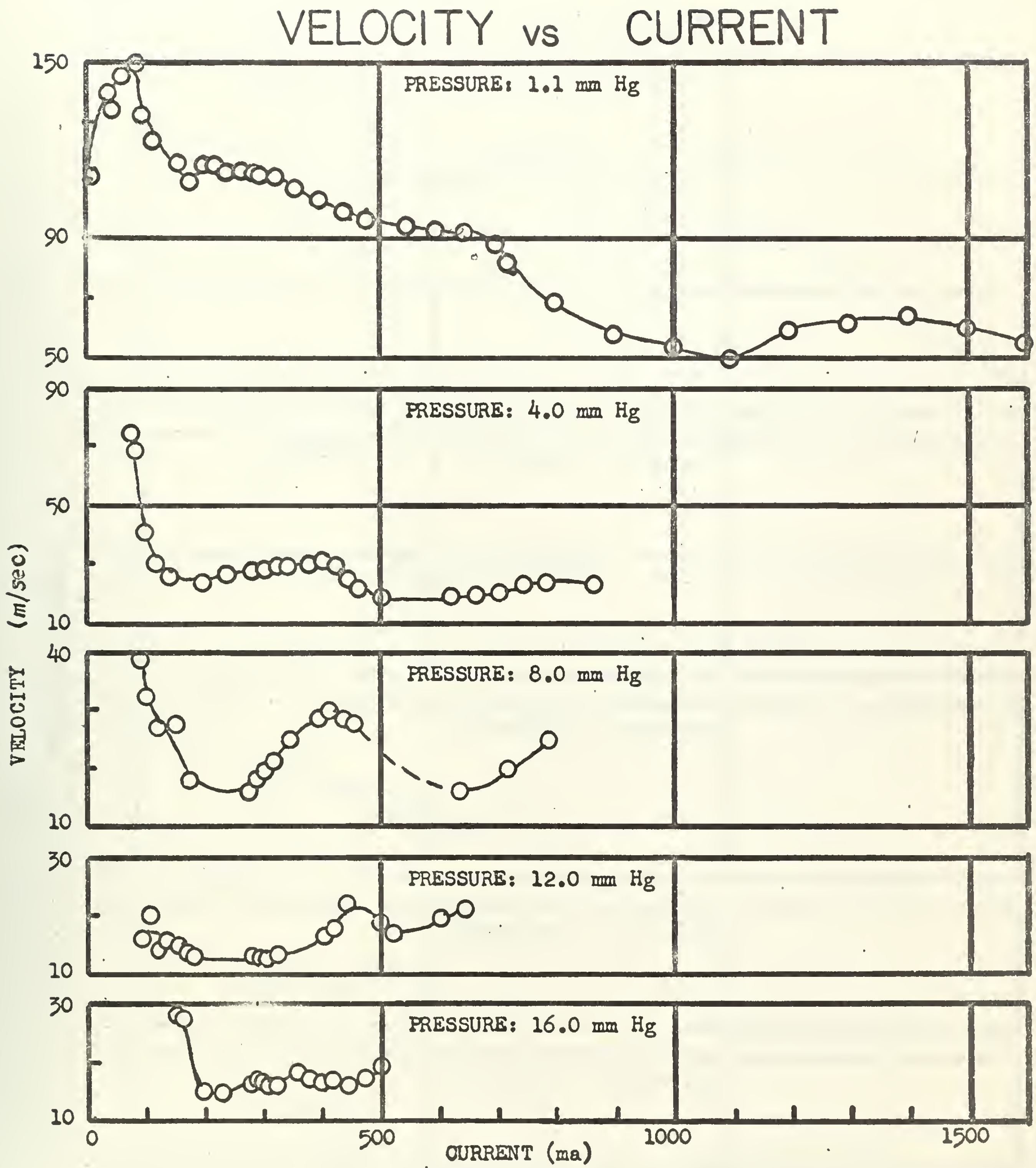


Figure 23

Argon, 2.10 cm Tube Radius

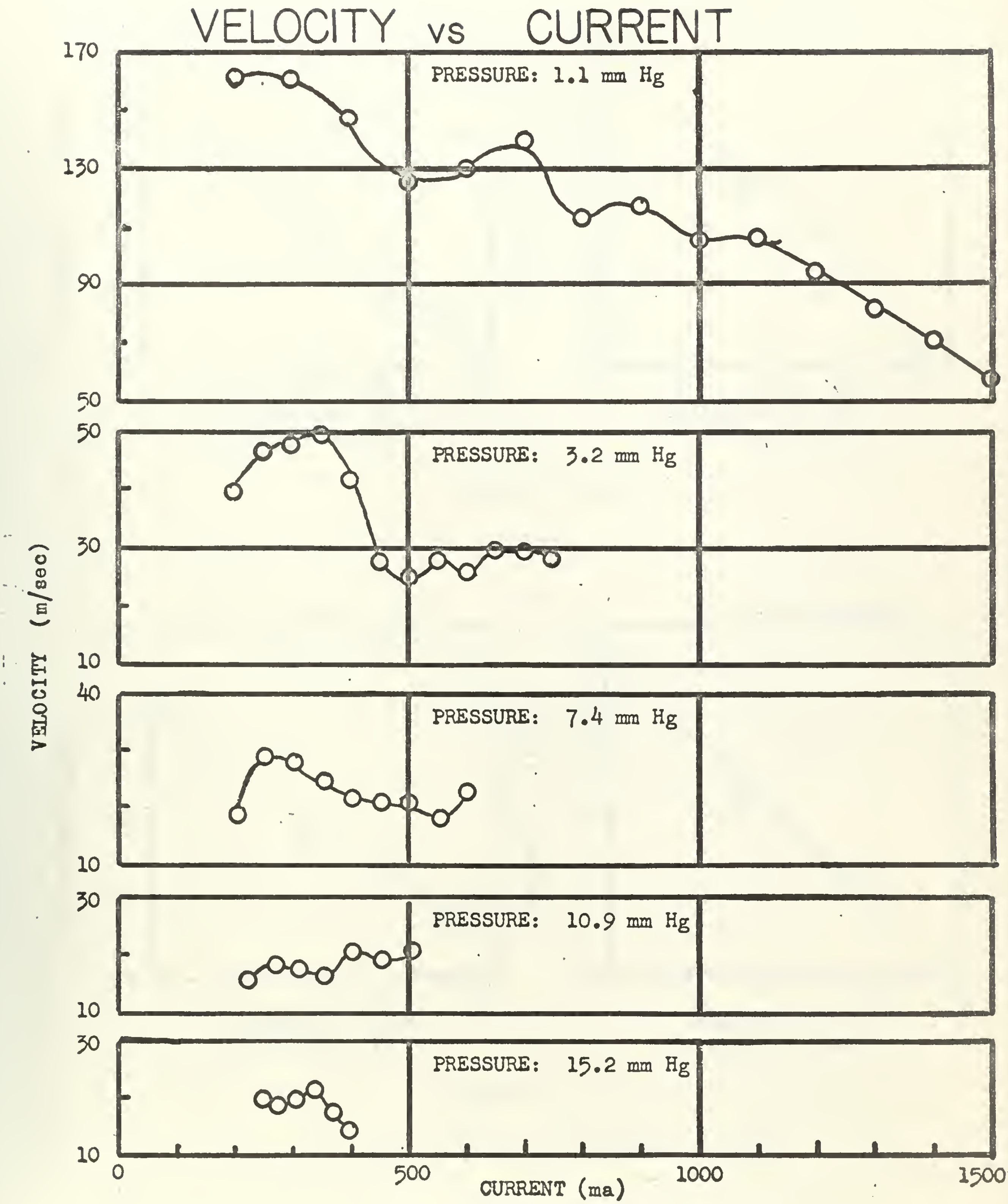
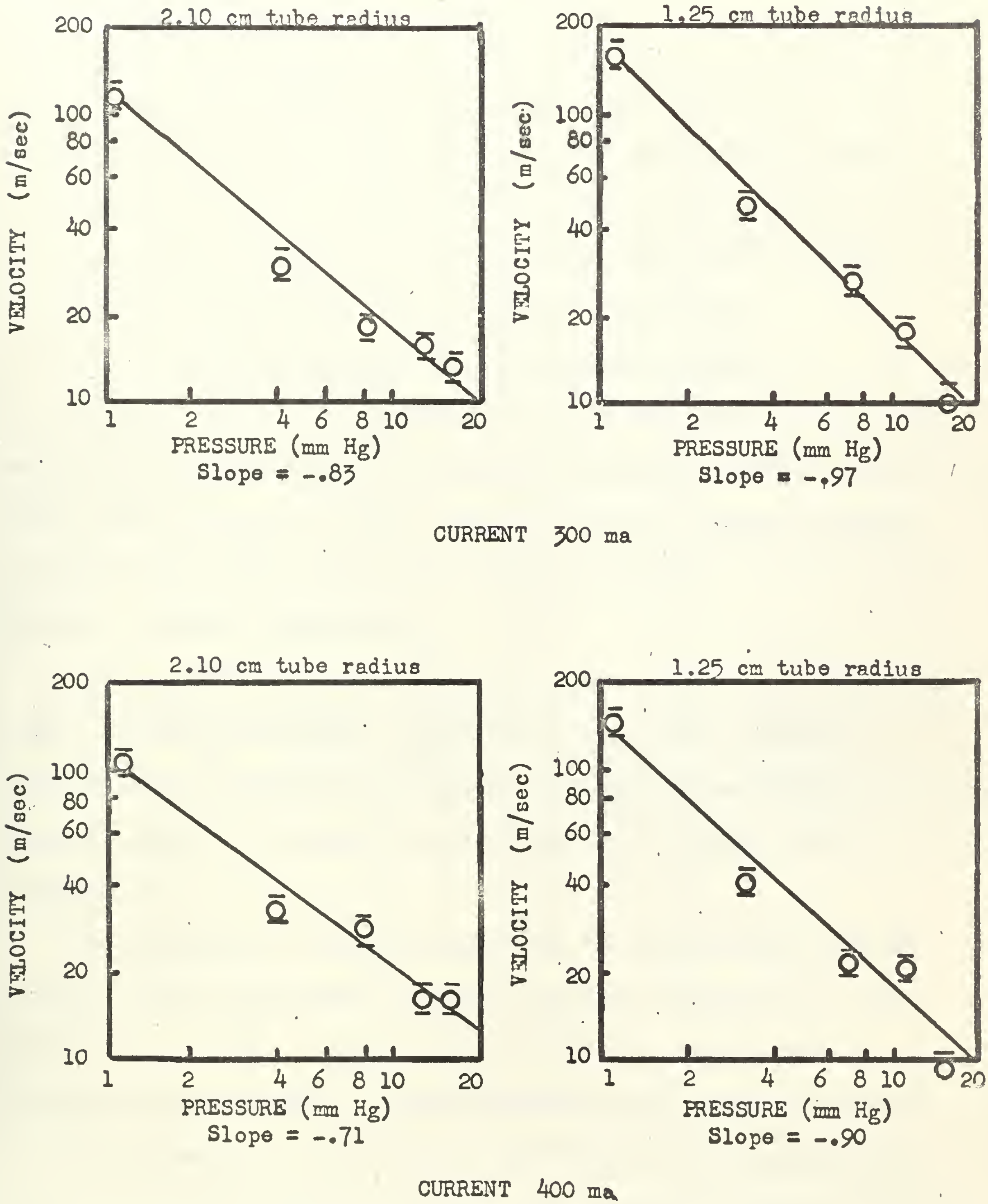


Figure 24

Argon, 1.25 cm Tube Radius

VELOCITY vs PRESSURE



Ξ Indicate estimated accuracy of ±10%

Figure 25

The graphs do not give conclusive proof as to the velocity being proportional to any specific power of the pressure, but only indicate a definite decrease in velocity with pressure. Based upon the four plots a proportionality to pressure to the minus 0.85 power might give a better empirical relation, for an approximate value of the velocity, but no such simple relation can adequately describe the behavior of the velocity of the striations with pressure.

3.4 Voltage Drop Across The Discharge Tube.

Figure 26 is a representative plot of tube voltage drop versus discharge current at various pressures. The potential drop across the tube, when operating a heated cathode is highly dependent upon the current supplied to the cathode and the cathode temperature.

The potential drop across this tube decreases regularly with increasing current. In general the tube voltage increases with increasing pressure although an exception is shown in the 1.1 mm and 3.2 mm pressures at about 550 ma current.

This apparent inconsistency led to examination of the voltage drop across Tube # 3 for various pressures at four different currents. Donahue and Dieke (7) found that the potential drop across the tube behaved in a similar manner to the frequency of the striations when plotted against the pressure in the discharge tube. The highest current at which data were reported was 70 ma.

Figure 27 shows the results of measurement of the voltage drop across the tube at various pressures. The minimum

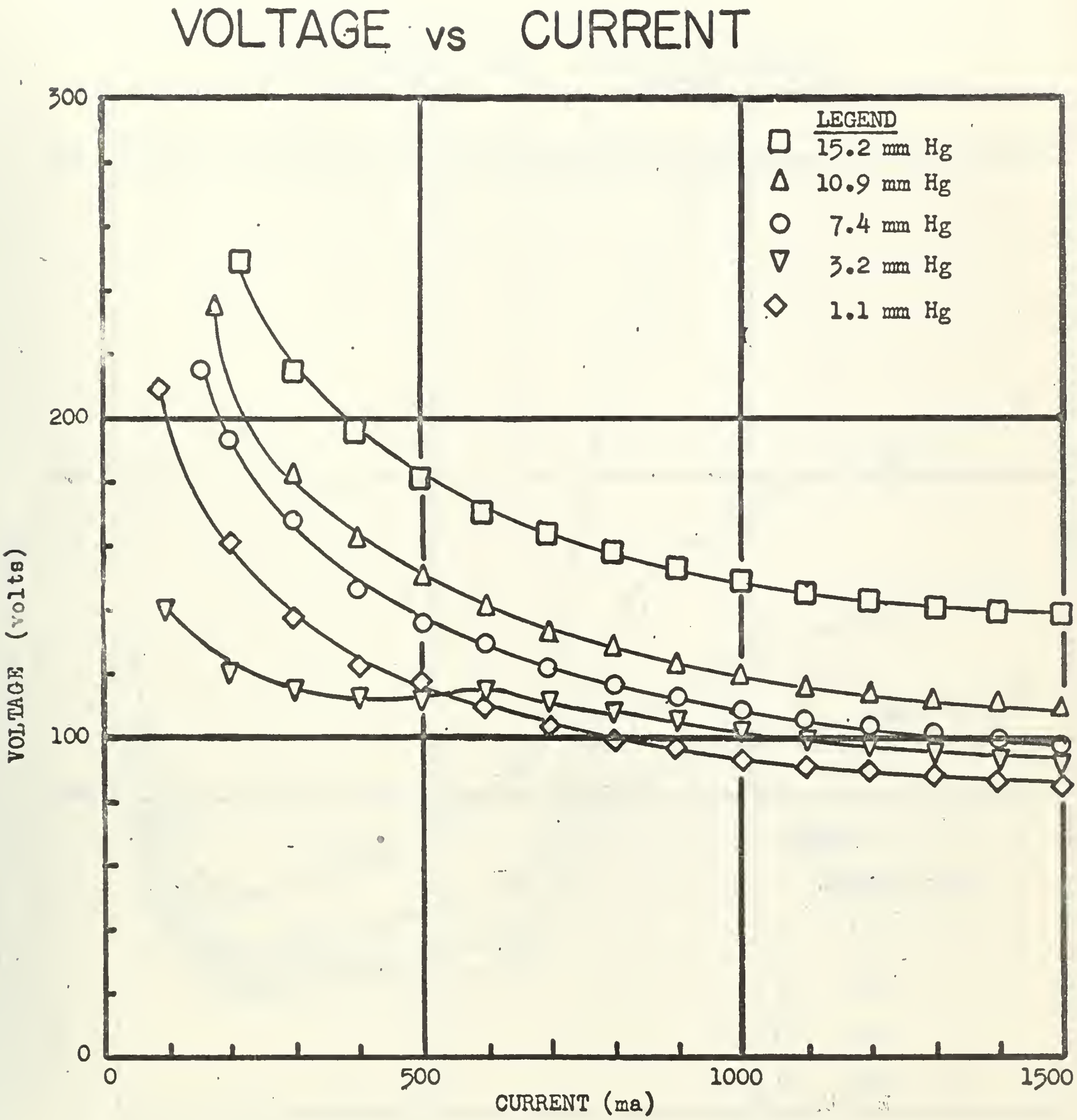


Figure 26

Argon, 1.25 cm Tube Radius

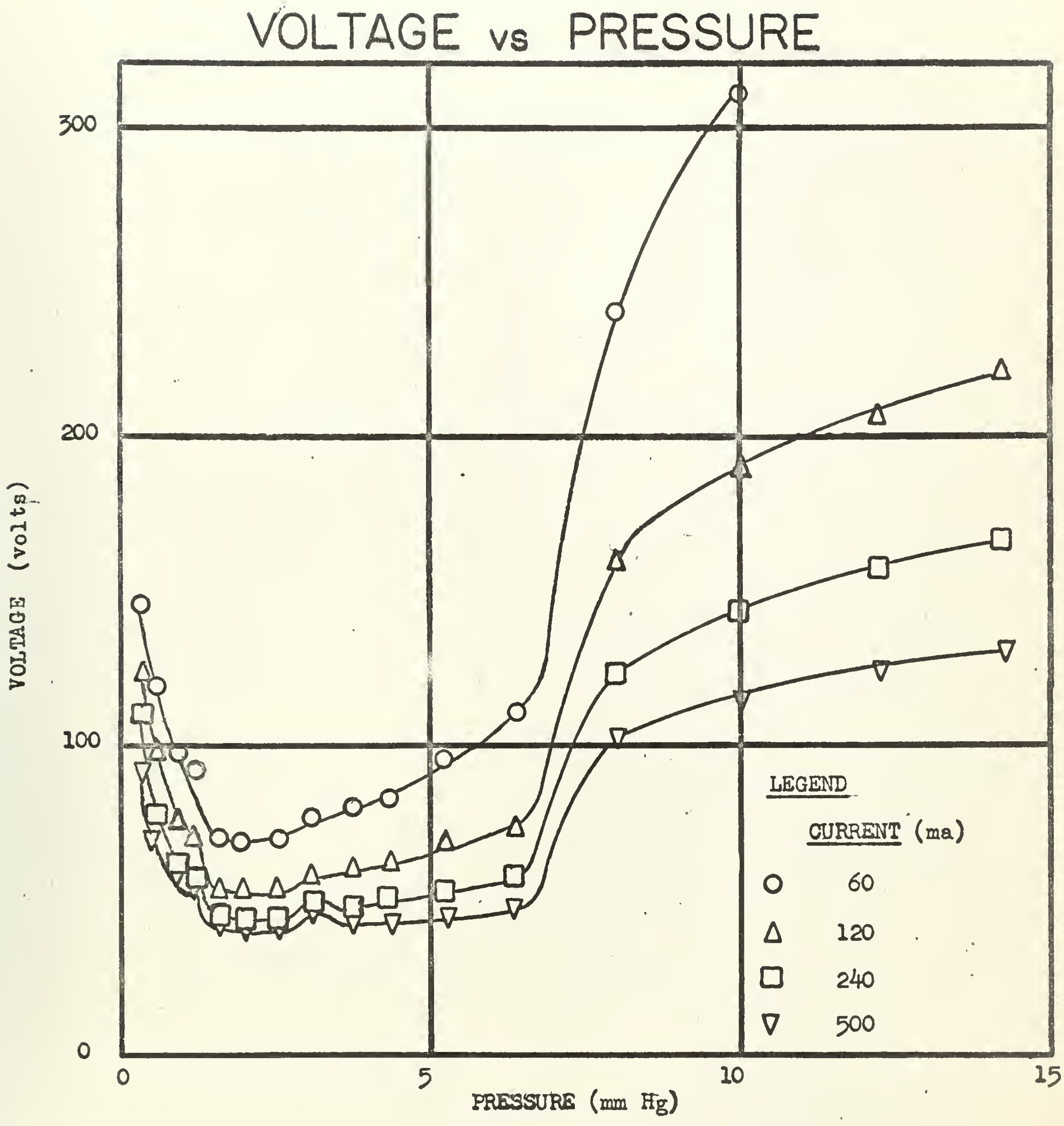


Figure 27

Argon, Tube #3

is exhibited at these higher currents and has become much broader. The minimum in the voltage versus pressure curve occurs at approximately the same pressure as the minimum in the frequency curve. The similarity between the voltage plot and the frequency plot is not so great as was found by Donahue and Dieke at lower currents.

4. OBSERVATIONS AND ANALYSIS OF PUPP'S ANODE TECHNIQUE.

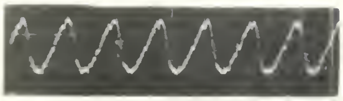
4.1 Effects on Moving Striations.

At all times during the course of our investigations the moving striation frequency and wave form were found to be entirely different from that of the anode spot light oscillations under normal discharge conditions. Figure 28 shows a sample comparison of simultaneous oscilloscope tracings of photomultiplier measurements.

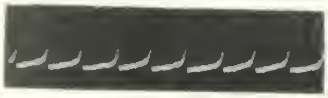
When the tube current is increased to above the cut off current for moving striations the anode spots remain after the extinction of the moving striations. In fact, we were unable to extinguish the anode spots at the maximum current our power supply could furnish. (2.25a) Trace (c), on a different time base from (a) and (b), shows the anode spots still present above the cut off current for moving striations. Trace (d), same time base and simultaneous with (c), shows the oscilloscope trace of the light intensity in the positive column, by means of a photomultiplier, after the tube current has been increased above the cut off current for moving striations. In the absence of moving striations there is a small oscillation of the light intensity of the positive column which has the same frequency, and is in phase with, the anode spot light oscillations. The magnitude of this oscillation is approximately one tenth that of the light oscillations due to the moving striations. The velocity of this wave form, if moving, was greater than 50,000 meters per second.

As shown above, the anode spot light oscillations,

a. Anode Spot Light Oscillations with Moving Striations present in the Positive Column.
i = 400 ma, 2 v/cm.



b. Light Oscillations of the Moving Striations in the Positive Column.
i = 400 ma, 2 v/cm.

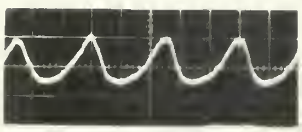


c. Anode Spot Light Oscillations with Moving Striations Extinguished in the Positive Column.
i = 850 ma, 5 v/cm.

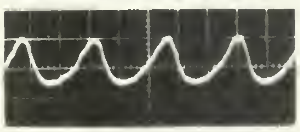
d. Light Intensity Oscillations of the Positive Column with Moving Striations Extinguished.
i = 850 ma, 5 v/cm.

Figure 28 - Light Oscillations of Anode Spots and Moving Striations

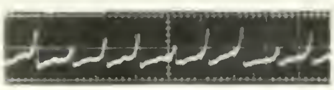
Argon, 8 mm pressure, 2.1 cm tube radius



a. Moving Striations with Anode Spots Present.
i = 150 ma, 0.1 v/cm.

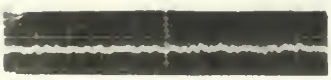


b. Moving Striations with Anode Spots Extinguished.
i = 150 ma, 0.1 v/cm.



c. Light Oscillations of the Anode Spots.
i = 150 ma, 0.1 v/cm.

d. Light Intensity of Anode Fall Region with Anode Spots Extinguished; note Moving Striations. i = 150 ma, 0.1 v/cm.



e. Light Intensity of Anode Fall Region with both Anode Spots and Moving Striations Extinguished. i = 630 ma, .05 v/cm.

Figure 29 - Photomultiplier Tracings of Moving Striations and Anode Spots with and without the Pupp's Anode Operating.

Argon, 9.5 mm pressure, 1.0 cm tube radius

which are here taken as evidence of an oscillating anode fall in potential, are not a sufficient condition for the production of moving striations. An attempt was made to eliminate the anode spot light oscillations, and thus the oscillations of the anode fall in potential, by use of an auxiliary discharge at the anode, and observe the effects upon the moving striations in the positive column.

Figure 29 (a), discharge current of 150 ma, shows the moving striations approximately 10 cm from the anode with anode spots present as shown by the photomultiplier trace (c). Trace (b) shows the striations, still present at the same location with a current of 60 ma in the Pupp's anode discharge. Trace (d), with the photomultiplier at the same location as (b), shows moving striations now present through the anode fall region and at the anode surface, with the same frequency as the moving striations in the positive column.

Trace (e), Figure 29, discharge current of 470 ma, shows the absence of both moving striations and anode spots when the discharge current is increased above the cutoff current for moving striations and the Pupp's anode is in operation.

On the basis of the above observations, it is concluded that the presence of anode oscillations in potential is not a necessary condition for the presence of moving striations.

The question still remains as to what disturbing effect, if any, the presence of oscillating anode spots has on the moving striations of the positive column. If they are not the originators of moving striations they might still have

a modulating effect. (Ref Sect 1.4, Fig 2) To answer this question measurements of the frequency of the moving striations versus discharge current were repeated in argon in a 2.97 cm radius tube at 1.1 mm Hg pressure over a current range of 280 ma to 720 ma; only this time the Pupp's anode was operated to extinguish the anode spots. A comparison of these data is shown in Figure 30.

The data obtained without the presence of anode spots follow closely the frequency data taken with anode spots present. In fact, the agreement is as good as has been usually obtained by repeating other runs where all conditions were the same. There are usually these small deviations due to uncontrollable changes in the discharge parameters. We can say for certain, however, that the frequency versus current characteristics were changed very little by the operation of the Pupp's anode. Wavelength measurements were made under the same conditions as above, and a comparison is shown in Figure 31. Here again the agreement was found to be quite good.

As an additional test, detailed frequency data was taken, with the Pupp's anode in operation, over a frequency maximum for argon at 12.5 mm pressure, over a current range of 100 to 300 ma. The comparison of the two sets of data is shown in Figure 32.

4.2 <u>Effects on Tube Voltage Oscillations</u>.

In all cases, when either moving striations and anode spots were present, the dc voltage between anode and cathode had an oscillating ac component of 5 to 7 volts superimposed

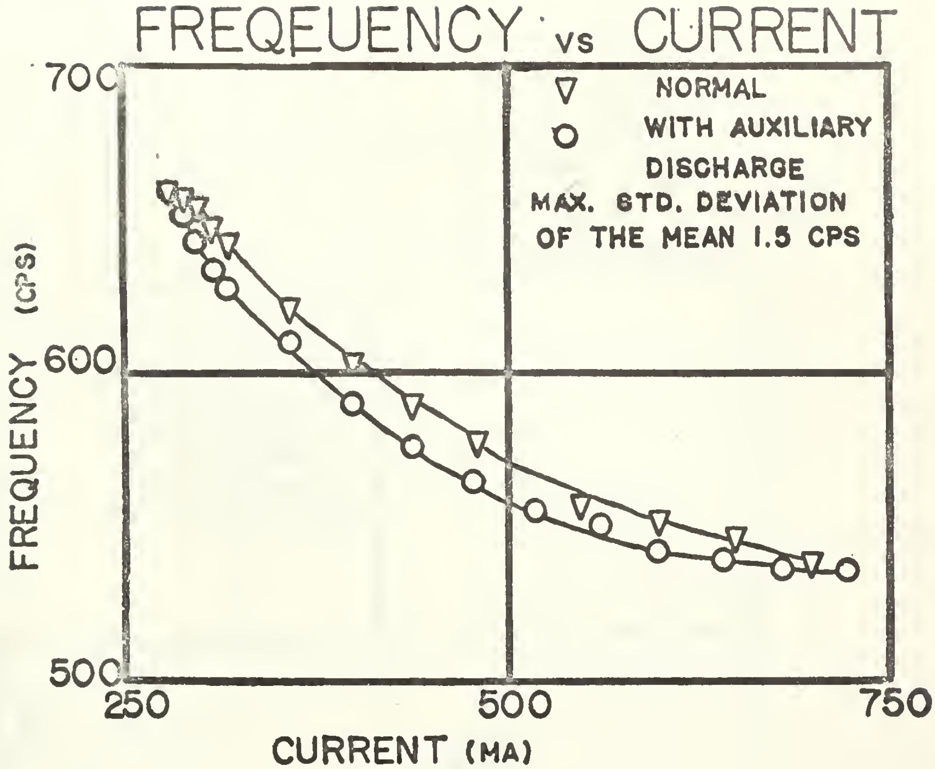


FIGURE 30

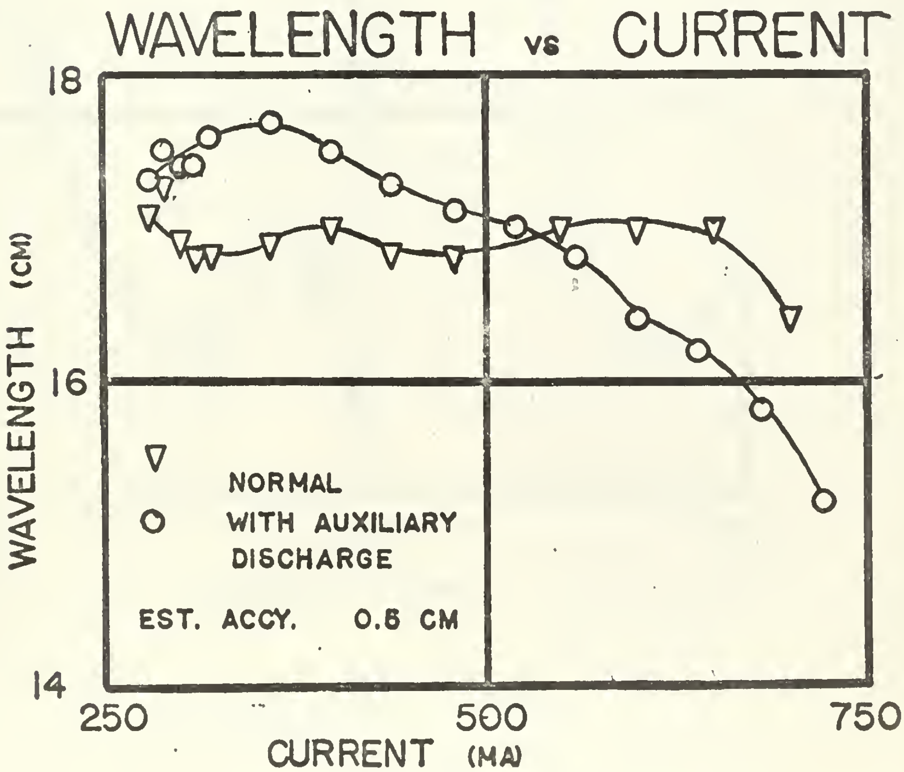


FIGURE 31

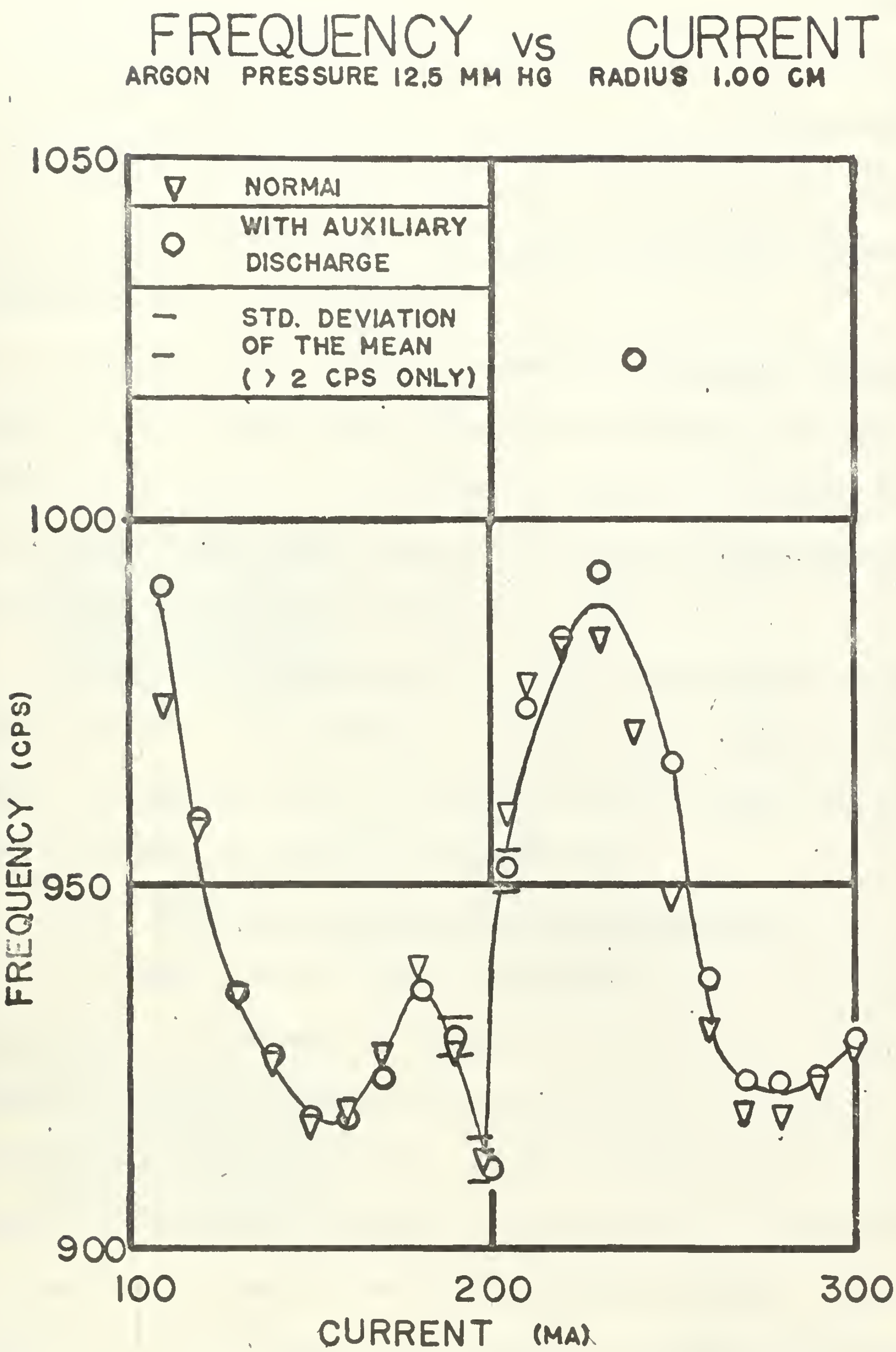

FREQUENCY vs CURRENT
ARGON PRESSURE 12.5 MM HG RADIUS 1.00 CM
NORMAl
WITH AUXILIARY DISCHARGE
STD. DEVIATION OF THE MEAN (> 2 CPS ONLY)
1050
1000
950
900
FREQUENCY (CPS)
100
200
300
CURRENT (MA)

FIGURE 32

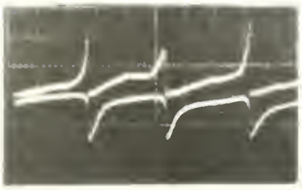
on it. This voltage oscillation was observed to have the same frequency and to be in phase with the anode spot light oscillations as shown in Figure 33. The upper trace shows the anode spot light oscillations as picked up by the photomultiplier and displayed upon the oscilloscope. The lower trace shows the voltage oscillation trace obtained by connecting the oscilloscope input between the anode and the cathode which is grounded.

If the Pupp's anode is used to eliminate the anode spot oscillations, then the voltage oscillations assume the wave form of the moving striations as shown in Figure 34. It is noted also that the voltage oscillations are reduced in magnitude by a factor of one-half or more.

If we now extinguish both the striations, by operating above the cut off current, and the anode spots, by use of the Pupp's anode, we see that there are no longer any voltage oscillations, as shown in Figure 35.

4.3 <u>Effects upon the Probe Oscillations</u>.

The tube used in these experiments was constructed with two probes, as shown in Figure 8, so that the floating potential of the positive column could be monitored. This was done by connecting the oscilloscope across the probe and ground (either the cathode or the anode was grounded depending upon which was to be our reference point). The floating potential of the positive column was found to have the same wave form and frequency as the voltage oscillations across the tube, as shown in Figure 36, lower traces of (b) and (c).

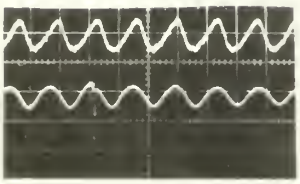


Upper: Anode Spot Light Intensities, 0.5 v/cm.

Lower: Tube Voltage Oscillations with Anode grounded, 5 v/cm.

Figure 33 - Showing the Phase Relation between the Anode Spot Light Oscillations and the Tube Voltage Oscillations

Argon, 5.4 mm pressure, i = 1160 ma.



Upper: Moving Striations in center of Positive Column, 0.1 v/cm.

Lower: Tube Voltage Oscillations with Anode grounded, 1.0 v/cm.

Figure 34 - Showing the Wave Form Correspondence between Moving Striations and Tube Voltage Oscillations with the Anode Spots extinguished

Argon, 11.2 mm pressure, 2.1 cm tube radius, i = 550 ma.

Upper: Light Intensity of Positive Column showing Moving Striations extinguished, 0.05 v/cm.

Lower: Tube Voltage with the Anode grounded, 0.05 v/cm.

Figure 35 - Showing the Absence of both Moving Striations and Tube Voltage Oscillations when the Anode Spots are extinguished with the Tube Current above Cutoff for Moving Striations

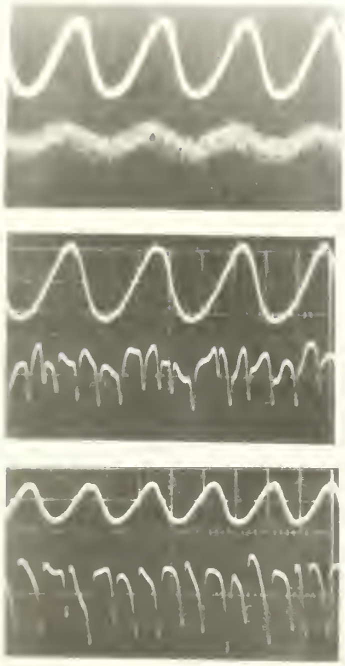
Argon, 11.2 mm pressure, 2.1 cm tube radius, i = 850 ma

It was also found that the amplitude of the floating probe potential is modulated by a superimposed wave form, that is in phase with the striation wave form at the same point of the positive column. (Figure 36 (a) and (b).) If the tube current is increased above the cut off current for moving striations the floating probe potential is no longer modulated as shown by Figure 37, Trace (a). If the oscillating anode spots are now extinguished with the Pupp's anode the floating probe potential becomes constant as shown in Trace (b).

4.4 Summary.

This study of tube voltage oscillations and floating probe potential oscillations of the positive column gives a picture of the mechanism of the oscillating anode fall region of the discharge, which appears to be in agreement with that proposed by Pupp (5). Let us consider the anode fall region at an instant of maximum positive ion concentration. This high positive space charge inhibits the electron flow to the anode from the positive column. This results in a reduced flow of electrons to the external circuit and a rise in potential of the anode.

The positive ions now drift away from the anode and more electrons are allowed to be accelerated to the anode. The current to the external circuit is increased with a resulting drop in anode potential. The increased electron flow to the anode increases the production of positive ions and a positive ion space charge builds up again to excess concentrations. The reason for the production of excess



[illegible]
Probe, [illegible] v/cm.

(a)

Lower: Floating Potential Oscillations of Probe (Scope on continuous sweep), 1 v/cm.

Upper: Striation Light Oscillations at Center Probe, 0.2 v/cm.

(b)

Lower: Floating Potential Oscillations of Probe (Scope on single sweep), 1 v/cm.

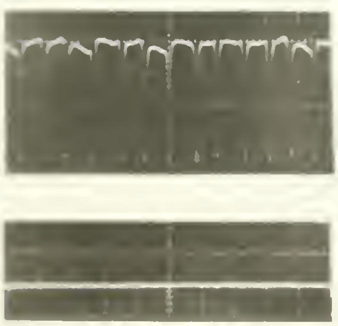
Upper: Striation Light Oscillations at Probe, 0.2 v/cm.

(c)

Lower: Tube Voltage Oscillations, 2 v/cm.

Figure 36 - Scope Tracings of Moving Striations, Probe Oscillations, and Tube Voltage Oscillations, with Anode Spots Present

Argon, 9.5 mm pressure, 3 cm tube radius, i = 260 ma.



a. Floating Potential Oscillations at Probe with Anode Spots Present, 2 v/cm.

b. Floating Potential at Probe with Anode Spots Extinguished, 0.05 v/cm, i (Pupp's Anode) = 60 ma.

Figure 37 - Scope Tracings of Floating Probe Oscillations with Moving Striations Extinguished

Argon, 9.5 mm pressure, 3 cm tube radius, i = 550 ma.

ions is not yet understood.

It does seem apparent that the current flow to the external circuit and thus the anode potential is principally governed by the anode fall region. If this is the case, it is then reasonable to expect that the modulation of the tube voltage oscillations by the striations in the positive column will be small. In the positive column the disturbing effect of the striations on the potential would be much more pronounced.

The presence of the auxiliary discharge in the anode fall region allows the positive column to extend to the anode surface; thus the only modulation of the current flow through the tube is produced by the disturbances from the moving striations.

At this point, the suggestion of Donahue and Dieke (6) that the movement of the positive space charge away from the anode is the origin of a moving striation must be rejected. It has been definitely shown that eliminating the oscillations of the anode fall region does not prevent moving striations from being present in the positive column. The absence of this anode oscillation has little or no effect upon the wavelength and frequency of the moving striations.

5. OBSERVATIONS AND ANALYSIS OF ISOLATED STRIATIONS.

5.1 Background.

Noting that in argon, the critical current for extinction of moving striations increases with an increase in tube radius, A W Cooper (18) concluded that if a discharge were run in a tube, with a section at a smaller radius than the remainder of the tube, a break in the striated column should appear. Cooper operated the tube at a discharge current above the current for extinguishing striations in the small center section and below the critical current for the larger sections and found there was no requirement for a striated column to be continuous. Figure 38 shows this tube. Striations were not observable in the section of the tube marked a, but were observable in both sections b and c. It is evident, from this experiment, that there is no requirement for a continum of moving striations through the positive column.

At the suggestion of Professor Cooper, experiments were conducted in a step tube which had the center section of the tube at a larger radius than the end sections. This tube is pictured in Figure 39.

This tube was used to test a requirement that the striations be continuous with the anode. It has been established previously that, as the current is increased toward cut off, the striations disappear first from the cathode end of the positive column and as the current is further increased the striated region shrinks steadily, disappearing last at the anode end of the positive column.

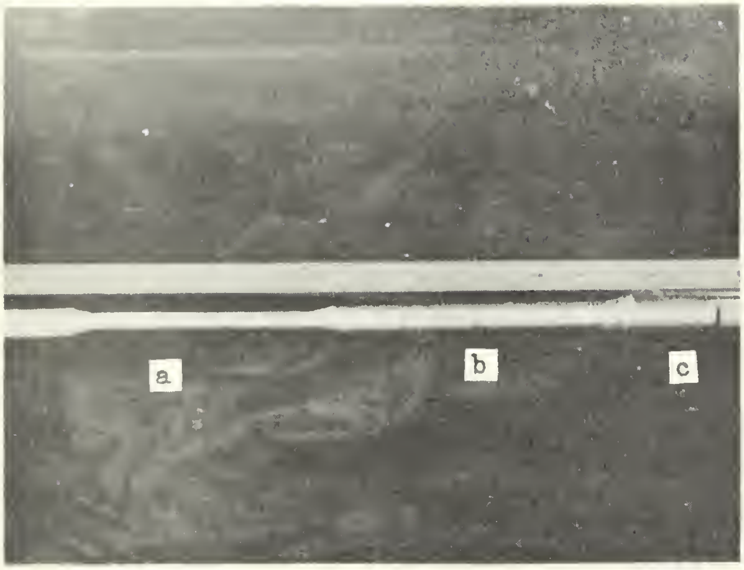


Figure 38 - Step Tube designed by A. W. Cooper to extinguish Moving Striations in the Small Diameter Center Section while still having Moving Striations in the Larger Diameter End Sections

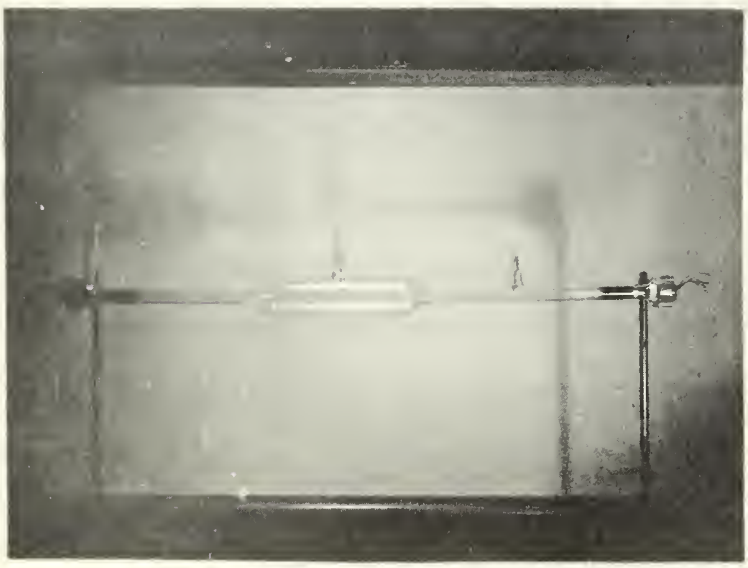


Figure 39 - Step Tube used in This Work to isolate Moving Striations to the Larger Diameter Center Section only

5.2 Striations Isolated From Both Anode and Cathode.

The experiment succeeded in producing moving striations in the larger radius center section while the end sections contained an unstriated positive column. Figure 40 shows a rotating mirror photograph of the isolated striations and Figure 41 shows the striations extending throughout the positive column.

One can see immediately that the wavelength, frequency and velocity of the striations have two distinctly different values, depending upon the local radius of the tube. Figures 14 and 15 show frequency versus pressure data in the two sections of the tube at two different currents. These plots show little, if any, coupling effect between the different radius sections. It appears that the striation frequency is primarily dependent upon the pressure of the gas, type of gas, tube radius, and discharge current through the positive column. It is also evident that there is no requirement for the moving striations to be connected with the anode fall region.

5.3 Voltage and Probe Oscillations.

Further experiments were conducted with the step tube to study the effects of the anode fall region on a small area of isolated striations in the center of the tube and also on the tube voltage oscillations and floating potential of the positive column at various points in the positive column.

First a comparison was made between the tube voltage oscillations and the floating probe potentials with

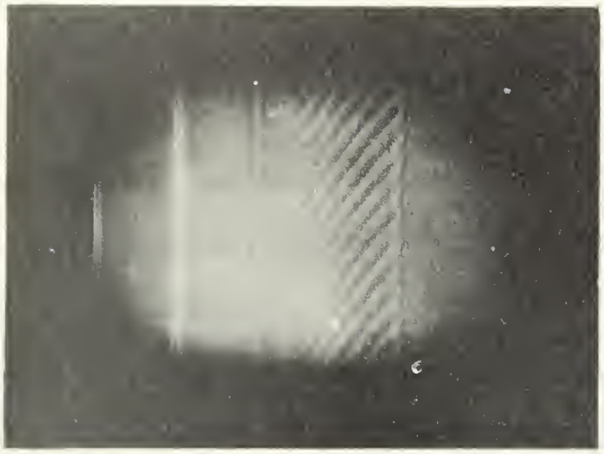


Figure 40 - Rotating Mirror Photograph showing Moving Striations Present only in the Large Diameter Center Section of the Step Tube

Argon, 9.5 mm pressure.

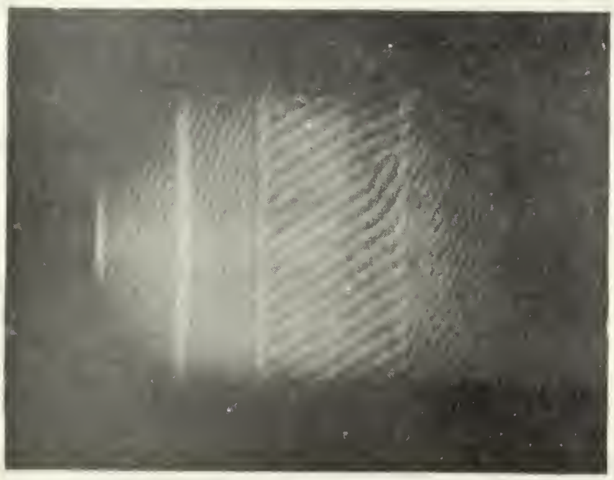


Figure 41 - Rotating Mirror Photograph showing Moving Striations Present in both the Center Section and the Smaller Diameter End Sections of the Step Tube

Argon, 9.5 mm pressure.

striations the entire length of the tube; then with striations only in the center section of the tube; with a very narrow band of striations in the center section of the tube, and finally with no striations detectable in the tube.

With striations the entire length of the tube the tube voltage oscillations followed the frequency of the anode spot light oscillations. (Figure 33) The floating potential of the positive column, in both the large and small radius sections, follows the frequency of the tube voltage oscillations, with the amplitude modulated by a wave form of the same frequency and phase as the striation wave form at the same point in the tube. (Figure 42 (a) - (m))

If the anode spots are eliminated with the Pupp's anode the tube voltage oscillations have a wave form that appears to be a superposition of the two wave forms from the striations in the different sections of the tube. (Figure 42 (n), (r), (v), and (z))

The probe oscillations in the large radius section are in phase with the striation wave form at that particular point. (Figure 42 (n), (p)) However, there is also a superimposed wave form that appears to be that of the striation wave form in the small radius section. (Figure 42 (o), (q)) The probe oscillations in the small section are in phase with the striation wave form at that point, with a superimposed wave form which appears to be of the frequency of the striations in the larger section. (Figure 42 (r) - (u), (w) - (y))

The current was then increased so as to have moving

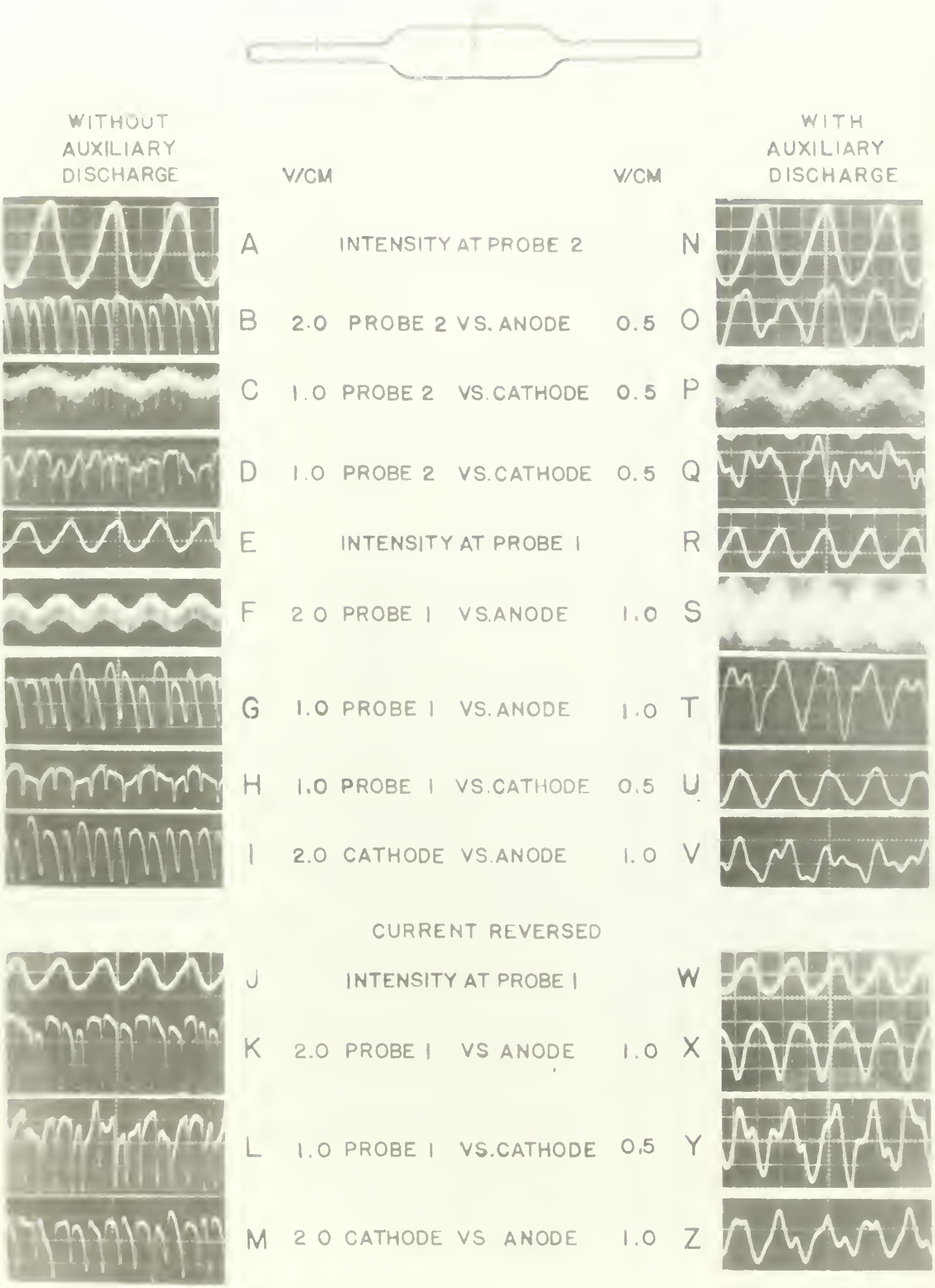


FIG 42 LIGHT INTENSITY AND FLOATING POTENTIAL WAVEFORMS IN TUBE 3
ARGON 9.5 MM HG. CURRENT 270 MA.

striations present in the entire center section, but extinguished in the smaller radius and sections. The tube voltage oscillations and the floating probe potentials followed the wave form of the anode spots with the center probe showing the superimposed striation wave form in phase with the striations at that point. (Figure 43 (a) - (c)) The probe in the small radius section showed no coherent superimposed wave form. ((d) - (h))

If the anode spots were eliminated with the Pupp's anode, it was found that the tube voltage oscillations followed approximately the wave form of the striations. (Figure 43 (j), (o)) The probe oscillations at the center section followed the wave form and were in phase with the striations at that point. (Figure 43 (j) - (l)) The probe in the small radius section, when measured versus the closest electrode, showed only a 0.03 volt oscillation which appears to be of the frequency striations would have in the small radius section if they were present. (Figure 43 (m), (q)) The probe potential in the small radius section, when measured versus the far electrode, i. e, across the striated region; and the tube voltage oscillations, showed a wave form that appears to be of the same frequency, but of the order of 0.3 volts. (Figure 43 (n) - (p))

When observations were made with the current adjusted so as to have striations in a small (approximately two inch) section at the anode end of the large radius section, the tube voltage oscillations and the probe oscillations all had the same frequency as the anode spot oscillations.

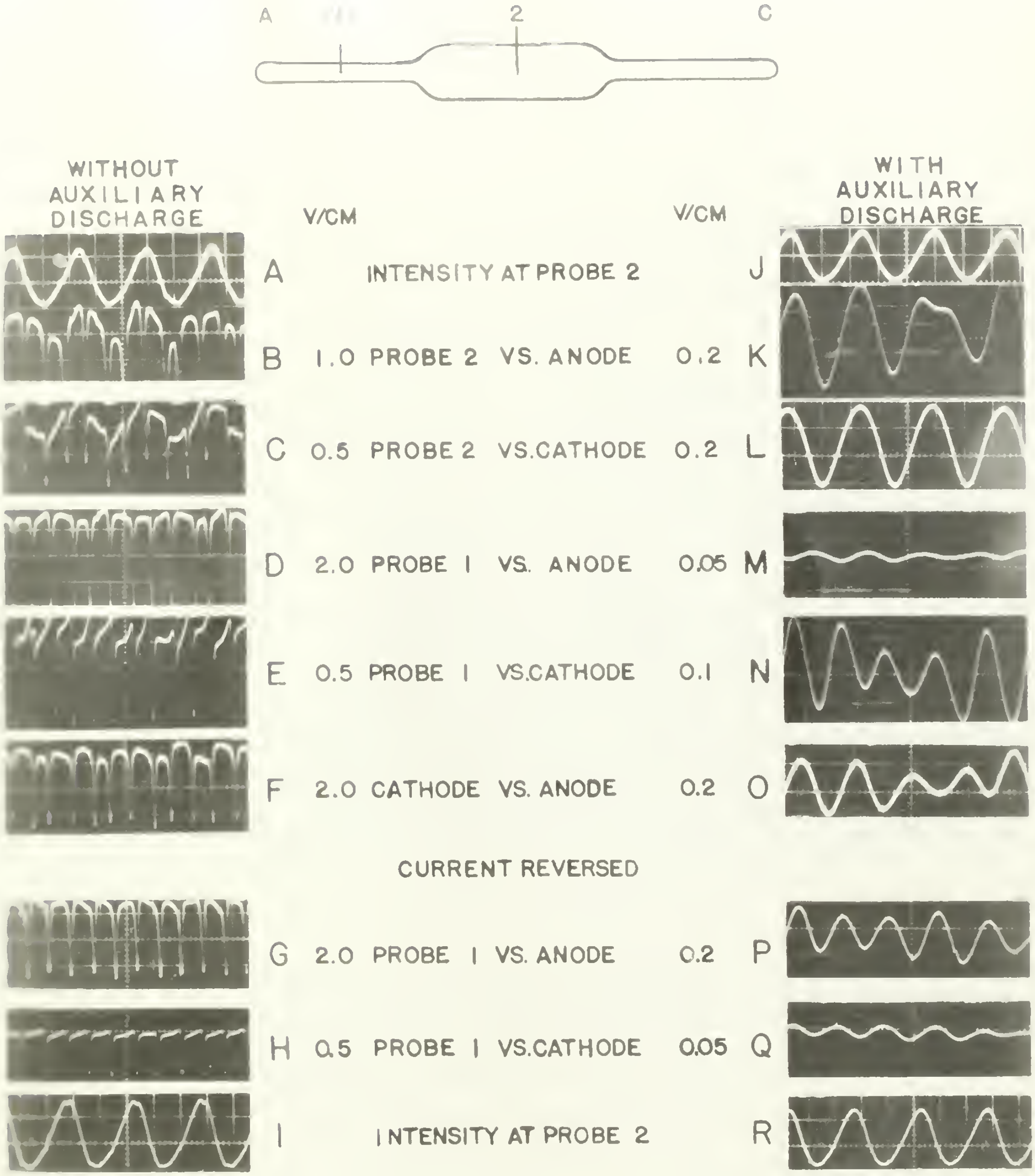


FIG. 43 LIGHT INTENSITY AND FLOATING POTENTIAL WAVEFORMS IN TUBE 3
ARGON 9.5 MM HG. CURRENT 475 MA.

(Figure 44 (a) - (h)) When the anode spots were eliminated, it was found that probe potentials and the tube voltage became constant. (Figure 44 (i) - (p)) If oscillations were present, their magnitude was less than 10 milli-volts.

This experiment has succeeded in producing moving striations that are confined to a small section of the positive column. This narrow region of moving striations produces no detectable modulation of the potential of other portions of the positive column or of the tube voltage.

When the current is increased to extinguish moving striations, throughout the entire length of the tube, the tube voltage oscillations and the potential of the whole positive column oscillates in phase with and at the same frequency as the anode spots. The light intensity of the whole positive column oscillates in phase with, and with similar wave form to, the tube voltage oscillations. (Figure (45) (a) - (f)) Extinguishing the anode spots eliminates all voltage and light oscillations throughout the tube. (Figure 45, (g) - (l))

5.4 Summary.

The studies of isolated striations produced strong evidence that moving striations are a local phenomenon in the positive column; the characteristics of the moving striations (frequency, wavelength, and velocity) depending on the tube radius, gas pressure, and current density of that portion of the positive column, and not upon the anode or cathode influence.

Moving striations and anode spots are two separate phenomena, but the modulating effect of both phenomena on the tube current and positive column potential are superimposed.

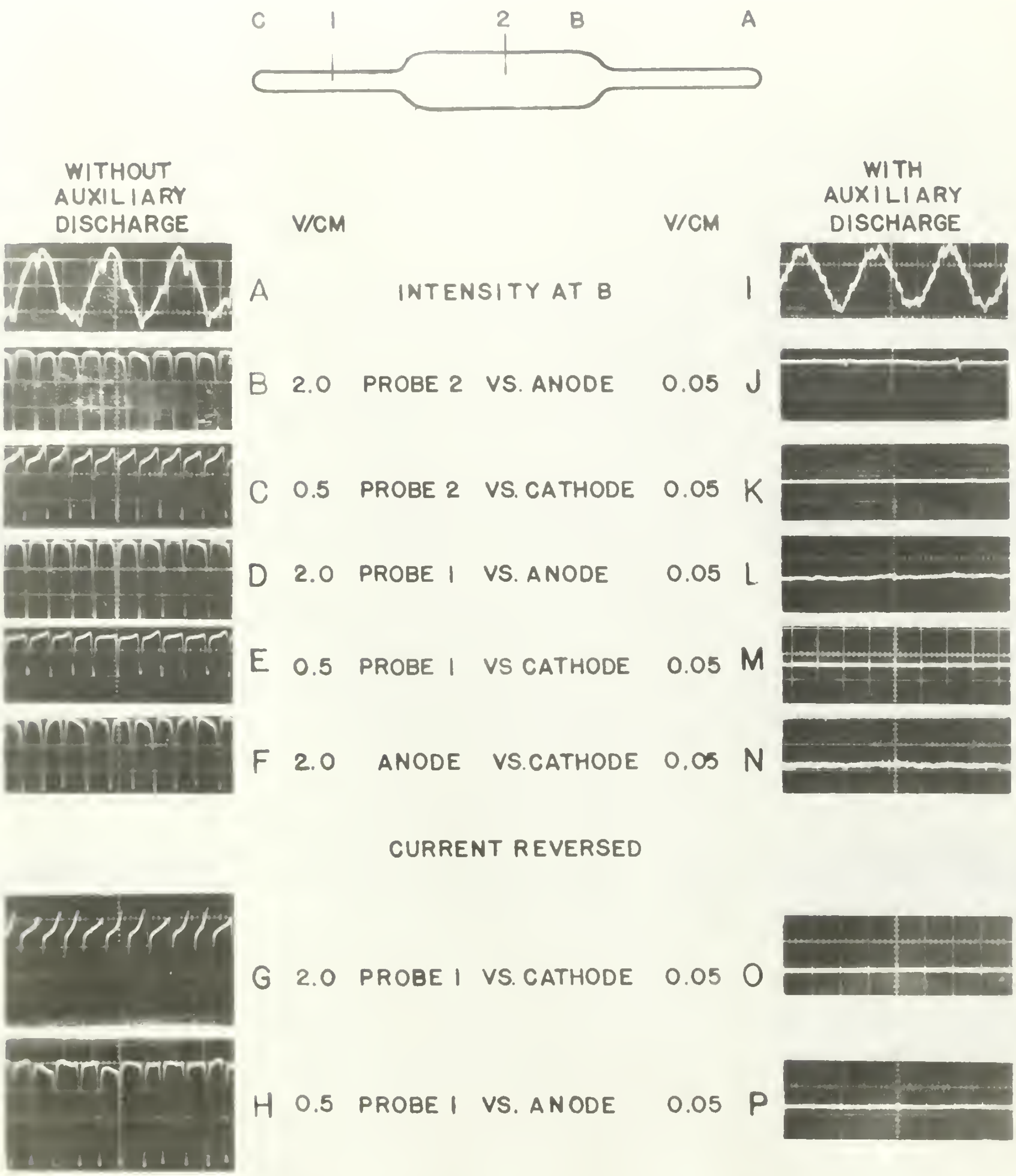
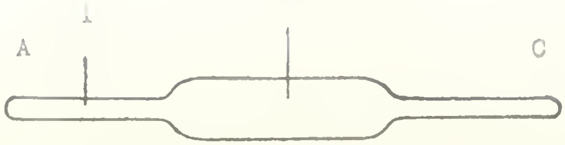


FIG. 44 LIGHT INTENSITY AND FLOATING POTENTIAL WAVEFORMS IN TUBE '3
ARGON 9.5 MM HG. CURRENT 550 MA.



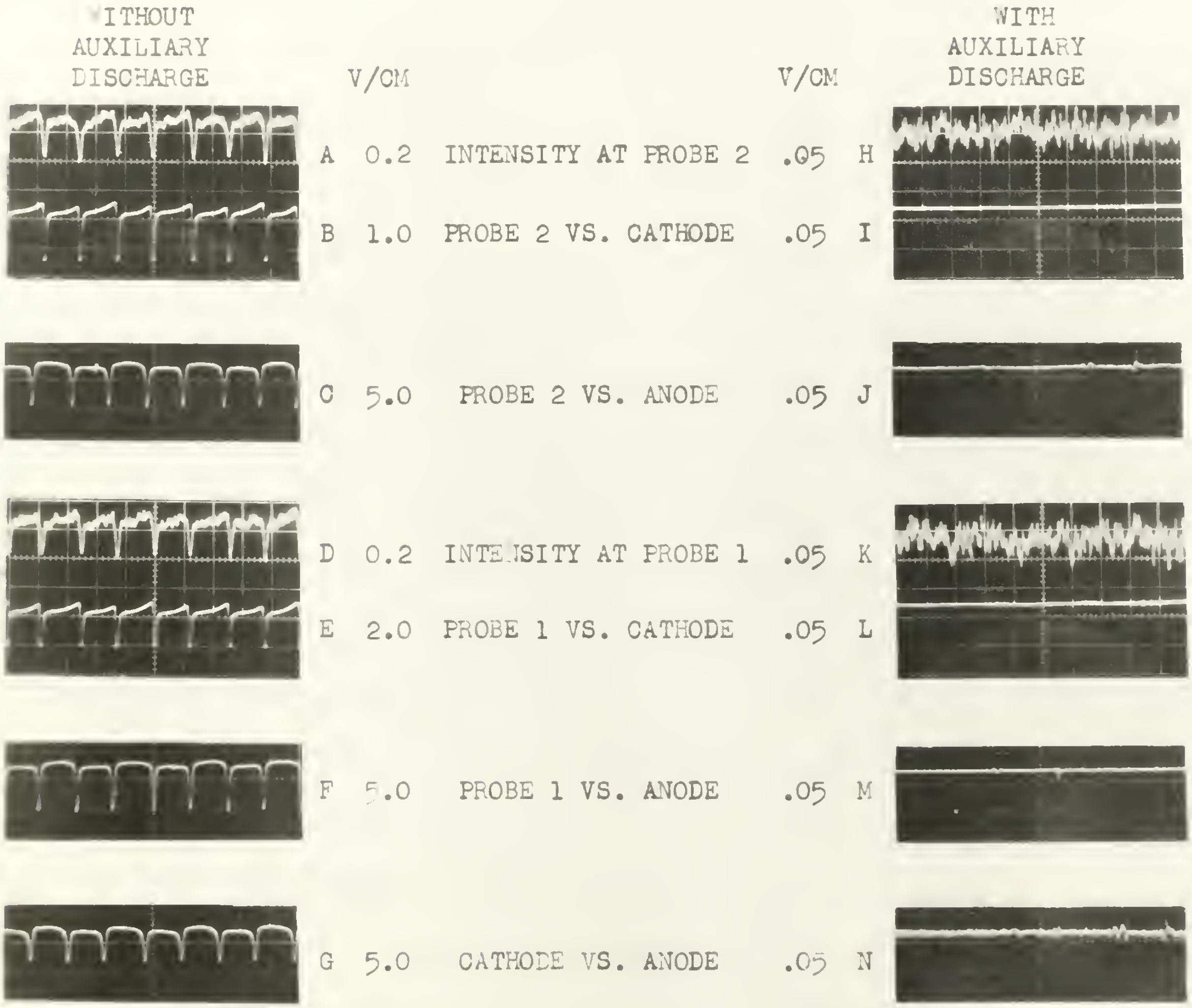


Figure 45 - LIGHT INTENSITY AND FLOATING POTENTIAL WAVEFORMS IN TUBE III

Argon, 9.5 mm Hg, current 700 ma.

6. CONCLUSIONS

6.1 Conclusions.

The work on basic parameters in Section 3 gives support to the data reported by Donahue and Dieke (4) and by Pupp (7). This is significant in that the data obtained in the present investigations were for differently constructed discharge tubes, with larger diameters than those used by these two earlier investigators. A more meaningful method of plotting striation frequency data was found. By plotting frequency versus pressure at a constant discharge current, with tube radius as the third parameter, an orderly family of curves resulted. Frequency plotted versus current was generally a decreasing function of current, but there were small maxima and minima, several times larger than the standard deviation of the mean for each point measured. This behavior is not indicated by any mathematical treatment thus far proposed for the positive column.

The similarity principle was tested by plotting the product of pressure times tube radius versus the product of frequency times tube radius. If the similarity principle applies to the positive column, all points will fall upon the same curve. Variation from a single curve at low currents and large tube radii, (Figure 20) leads to the conclusion that some other processes, such as two stage ionization, metastable state production, and collisions of the second kind are important in the production of moving striations at these low currents and larger tube radii.

The investigation of the oscillating anode fall region,

in Section 4, produced evidence that the anode spots and the moving striations are two separate phenomena. Their effects can couple together in the modulation of the discharge current, but either can exist in the absence of the other. Striation parameters, such as frequency, wavelength, and velocity, are relatively unaffected when the anode spots are extinguished with the Pupp's Anode. This evidence appears to be conclusive that moving striations are not initiated by conditions in the anode fall in potential.

In Section 5, moving striations were investigated in a step tube. The moving striations were isolated to a region as small as a few centimeters in the central portion of the positive column. These isolated striations were unaffected by extinguishing the anode spots. It is concluded that the moving striations are localized phenomena arising from particular conditions of current density, tube radius, and type of gas present, at each point in the positive column.

Based upon the above observations, indicating little or no dependence of striation parameters upon the anode or cathode effects, no support can be given to theoretical treatments which require an excitation or interaction with an electrode region. (Ref Sect 1.4) The proposals of Robertson (13) appear to be consistent with these results.

6.2 Recommendations for Future Work.

Since it appears probable that metastable states are directly connected with the production of moving striations, it is reasonable that a detailed study should be made of the effects on the moving striations of varying the metastable

state concentrations. This can be accomplished by exposing the positive column to radiation of the proper frequency to excite the first metastable state to the next higher energy level from which transitions to the ground state are possible. The metastable state concentrations can be monitored by pulse sampling techniques so that the amount of radiation absorbed at various points in the striation cycle can be measured.

It was noted that if the positive column was drawn to the wall of the discharge tube with a magnet, the moving striations were extinguished in the portion of the positive column in contact with the tube wall. The moving striations remained unaffected in the other portions of the positive column. This leads one to speculate that a longitudinal magnetic field could be used to confine the positive column and that the resulting effect would be the same as increasing the tube radius by decreasing the diffusion to the walls of the tube.

6.3 Acknowledgments.

The authors are deeply indebted to Professor A. W. Cooper for his skillful guidance, inspired counsel, and enthusiastic interest in their work. They are also grateful for his generous assistance in the maintenance of the vacuum systems. The authors wish also to acknowledge the assistance of the technicians of the Physics Department.

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